Meeting Climate Change Targets:

The Role of Nuclear Energy

NEA
NUCLEAR ENERGY AGENCY

Nuclear Technology Development and Economics

Meeting Climate Change Targets

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;

– to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

Cover photo: Globe resting on moss in a forest (Romolo Tavani, ShutterStock).

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CCUS	Carbon capture, utilisation and storage
ESG	Environmental Social and Governance
GFR	Gas-cooled fast reactor
GIF	Generation IV International Forum
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelised cost of electricity
LFR	Lead-cooled fast reactor
LWR	Light water reactor
MMR	Micro-modular reactor
MSR	Molten salt reactor
NEA	Nuclear Energy Agency
SFR	Sodium-cooled fast reactor
SMR	Small modular reactors
VHTR	Very high temperature reactor
VRE	Variable renewable energy

Executive summary

Governments around the world have identified the climate crisis as one of the defining challenges for this generation and an existential threat (US Department of Defense, 2021; UN, 2021a). Climate experts have stated that climate change is widespread, rapid and intensifying and the strong, rapid, and sustained reductions in greenhouse gas emissions required to meet Paris Agreement emissions reductions targets are not on track (IPCC, 2021).

The magnitude of the challenge should not be underestimated. If the rise in mean global temperatures is to be limited to 1.5°C over pre-industrial levels by the end of the century, the planet has a "carbon budget" of 420 gigatonnes of carbon dioxide emissions (Raupach et al., 2014). However, rather than the steep reductions scientists had hoped for, global emissions are now expected to rise 16% by 2030 compared to 2010 (UN, 2021b). If net carbon emissions are to peak within the next few years and be reduced to zero by 2100 (or sooner), policy changes around the world as well as massive investments in innovation, infrastructure, and deployment of non-emitting energy resources will be required. More specifically, electricity systems will need to be decarbonised; vehicle fleets must be electrified or transitioned to non-emitting fuels; and a range of industrial sectors (e.g. off-grid mining, buildings, chemicals, iron and steel, cement, oil and gas) must all be transformed as well.

All credible models show that nuclear energy has an important role to play in global climate change mitigation efforts (e.g. IEA, 2021; BNEF, 2021; IIASA, 2021). Despite clear analyses from many sources, including the NEA, that point to the need for a massive, "all-the-above" approach that includes nuclear energy, some multinational activities, financial institutions, and policy makers avoid discussion of nuclear energy. This dynamic is deeply problematic to the cause of carbon reductions. All low-carbon technologies, including nuclear energy must be included in relevant discussions about the energy transition in order to maintain the integrity and evidence base of the policy dialogue. Without a significant contribution from nuclear energy, the prospects for meeting Paris targets will be significantly lower. The IEA, for example, estimates that it would cost the world an estimated USD 1.6 trillion more to meet Paris targets without nuclear energy (IEA, 2019). Ultimately, even this estimate may prove optimistic.

Today, nuclear energy supplies approximately 10% of the world's electricity from 444 nuclear power reactors in operation worldwide providing 394 GWe of capacity. Nuclear energy is the largest source of non-emitting electricity generation in OECD countries and the second largest source worldwide (after hydroelectric power). There are around 50 more commercial nuclear reactors under construction, which will provide an additional 55 gigawatts of capacity, and more than 100 additional reactors planned. Existing nuclear capacity displaces 1.6 gigatonnes of carbon dioxide emissions annually and since 1971 has displaced 66 gigatonnes of carbon dioxide – the equivalent of two years of global emissions (NEA, 2020a).

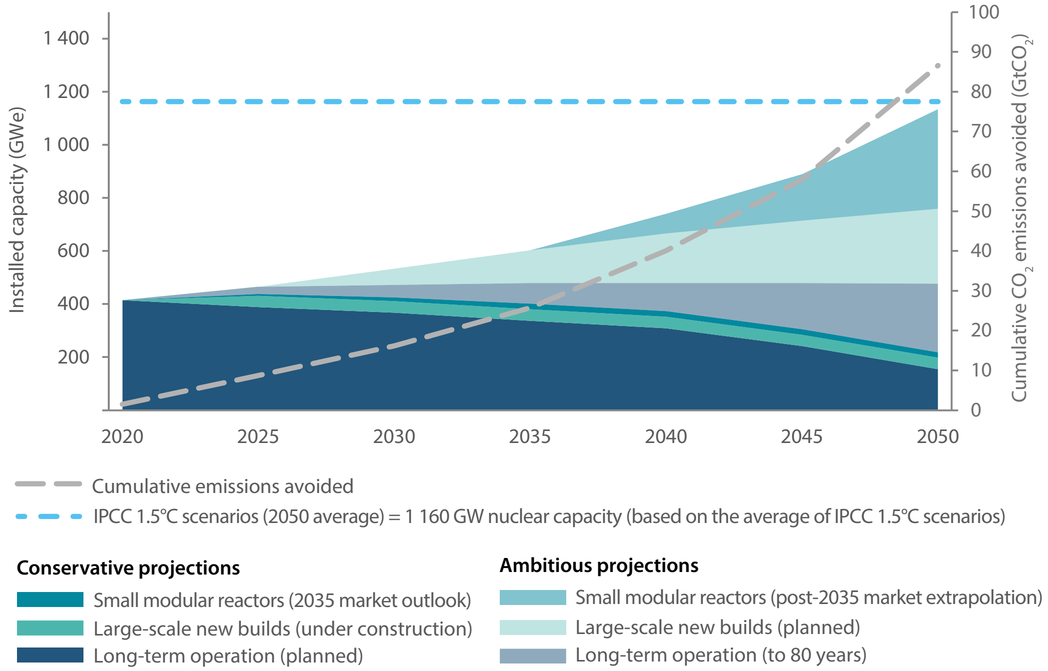
The nuclear energy sector can support future climate change mitigation efforts in a variety of ways. Existing global installed nuclear energy capacity is already playing a role and its long-term operation can enable the existing fleet to continue making a contribution for decades to come. There is also significant potential for large-scale Generation III nuclear new builds to provide non-emitting electricity in existing and embarking nuclear power jurisdictions, in particular to replace coal power.

Perhaps even more importantly, a wave of near-term and medium-term nuclear innovation has the potential to open up new opportunities with advanced and small modular reactors (SMRs), some of which are expected to be on the market before the end of this decade. In addition to electricity production, these technologies can support hybrid energy systems and applications including (but not necessarily limited to) sector coupling, combined heat and power (cogeneration) for heavy industry and resource extraction, hydrogen and synthetic fuel production, desalination, and off-grid applications.

In 2018 the IPCC considered 90 pathways consistent with a 1.5°C scenario – i.e. pathways with emissions reductions sufficient to limit average global warming to less than 1.5°C. The IPCC found that, on average, the pathways for the 1.5°C scenario require nuclear to reach 1 160 gigawatts of electrical capacity by 2050, up from 394 gigawatts in 2020 (IPCC, 2018).

This is an ambitious target for nuclear energy, but it is not beyond reach. It can be achieved through a combination of the long-term operation of existing plants and future deployment of Generation-III new builds, and small modular and Generation IV reactors, as illustrated in Figure ES1.

Figure ES1. **Full potential of nuclear contributions to net-zero**



New analysis by the NEA identifies the potential contribution of nuclear energy to clean energy capacity and emissions reductions between 2020 and 2050, taking into consideration the potential contributions from power and non-power applications of nuclear technologies.

Taken together, the contributions of long-term operation, new builds of Generation III nuclear technologies, small modular reactors, Generation IV systems, nuclear hybrid energy and hydrogen systems begin to reveal the full extent of the potential for nuclear energy and nuclear innovations to play a significant and growing role in pathways to net-zero by 2050.

Table ES1. **Projected contributions of nuclear energy to cumulative emissions reductions (2020-2050)**

Cumulative emissions* avoided from…	…electricity	…heat	…hydrogen	Totals
…long-term operation	38.3	6.7	4.3	49.2
…new builds of large Generation III reactors	16.2	4.2	2.4	22.8
…small modular reactors (SMRs)	9.7	3.6	1.8	15.1
Totals	**64.1**	**14.5**	**8.5**	**87.1**

* All cumulative emissions from 2020 to 2050 are shown in gigatonnes of carbon dioxide ($GtCO_2$).

Reaching the target of 1 160 gigawatts electrical capacity would avoid 87 gigatonnes of cumulative emissions between 2020 and 2050, preserving 20% of the world's carbon budget consistent in a 1.5°C scenario. This would be equivalent to avoiding nearly three years of global carbon emissions at 2020 levels.

Sufficient uranium resources exist to support continued use of nuclear power and significant growth in nuclear capacity for low-carbon electricity generation and other uses (e.g. heat, hydrogen production) in the long term. Identified recoverable resources, including reasonably assured resources and inferred resources (at a cost <USD 260/kgU, equivalent to USD 100/lb U_3O_8) are sufficient for over 135 years. Considerable exploration, innovative techniques and timely investment will be required to turn these resources into refined uranium ready for nuclear fuel production and to facilitate the deployment of promising nuclear technologies.

While the potential exists for nuclear energy to play a much larger role in global climate change mitigation efforts, various enabling conditions must be met. The above estimates are not forecasts but represent what can be achieved with timely enabling decisions.

To seize the window of opportunity, the nuclear sector must move quickly to demonstrate and deploy both near-term and medium-term innovations including Generation IV and small modular reactors, as well as nuclear hybrid energy systems including hydrogen.

Additionally, there are key enabling conditions for success that the nuclear energy sector and policymakers more broadly should address in the areas of system costs, project timelines, public confidence and clean energy financing.

A systems approach is required to understand the full costs of electricity provision, and to ensure that markets value desired outcomes: low carbon baseload, dispatchability, and reliability.

Rapid build-out of new nuclear energy is possible, but requires a clear vision and plan. Historical and recent experience show that under the right policy frameworks and a robust programmatic approach, nuclear energy can be a low-carbon technology with rapid delivery times. This was the case historically for countries such as France and Sweden and jurisdictions such as Ontario in Canada that have both decarbonised their electricity mix in less than two decades with nuclear energy and hydropower. Today, the Barakah project in the United Arab Emirates (UAE) demonstrates that such rate of deployment can also be achieved with large Generation III nuclear reactors. In China and Korea, countries in more advanced stages of nuclear energy construction learning, construction lead-times are around an average of 5-6 years, or even lower.

Building and maintaining public confidence is essential for all nuclear energy projects, from mining to research and development, operations, and waste management. Building trust is central to building public confidence and requires sustained investments in open and transparent engagement as well as science communication. A common mistake, however, is to assume that public confidence is primarily a communications issue, when in actuality, public confidence is much more complex, touching on issues of trust, values, culture and benefits sharing, among others.

Governments have a role to play in all capital-intensive infrastructure projects – including but not limited to nuclear energy projects. This role can include project financing, but also enabling policy frameworks that allow an efficient allocation of risks and for nuclear energy projects to compete on an equal footing with other non-emitting energy projects.

Policy recommendations

1. Act now

- *Governments* and *industry* should work together on an urgent basis to demonstrate and commercially deploy nuclear energy innovations before the window of opportunity closes to meet the 1.5°C target.

2. Understand and reduce costs

- The *nuclear energy sector* should implement recommendations from the NEA study *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders* to ensure that the sector meets cost objectives (NEA, 2020).
- *Governments* should take a systems level perspective when developing electricity policies to ensure that markets value desired outcomes, such as low carbon baseload, dispatchability and reliability.

3. Address timelines

- *Governments* and *industry* should learn from successful examples of rapid deployment of nuclear energy to decarbonise electricity grids, such as France, Sweden and Ontario (Canada) in the 1980s and the UAE from 2010 to the present. These examples chart a path for rapid decarbonisation of electricity grids that are still heavily reliant on coal and other fossil fuels.
- *Regulators* should collaborate to harmonise licensing approaches to enable efficient fleet deployment of nuclear innovations across international boundaries.

4. Build public confidence

- *Governments* and *industry* should engage their citizenry to build trust and public confidence, ensuring that public dialogue about energy options are evidence-based. This involves addressing misinformation and ensuring that a realistic conversation about the pros and cons of various options is facilitated.

5. Underpin investment

- *Governments* should support a technology neutral approach that includes nuclear energy in taxonomies, climate finance, development finance, and ESG finance.
- *Governments* should make investments in nuclear energy, including:
  - Investments to keep the cost of capital low;
  - Investments focused on accelerating commercialisation of nuclear innovation (focused on pre-commercial technology readiness levels 3-7);
  - Investments in nuclear regulators to ensure their readiness to regulate innovation; and
  - Equity investments as well as other forms of investment in near-term nuclear new build projects.

6. Ensure full representation in policy discussions about clean energy and climate change

- *Governments* should break the silence on nuclear energy in policy discussions about clean energy and climate change, raising the profile of nuclear energy alongside other non-emitting energy technologies and ensure that nuclear is included in discussions at climate change conferences. Three key messages are of particular importance:
  - **Nuclear energy already makes an important contribution to emissions reductions and it needs to expand to meet Paris Agreement targets**. Today, nuclear energy provides 10% of the world's electricity as the largest source of non-emitting electricity in OECD countries and second largest source of non-emitting electricity around the world, displacing 1.6 gigatonnes of carbon dioxide annually. The average IPCC 1.5°C scenario requires nuclear to reach 1 160 gigawatts of electricity by 2050, up from 394 in 2020.
  - **Near-term nuclear innovations are expected to make significant contributions to emissions reductions targets**. Nuclear innovation in the areas of advanced and small modular reactors (SMRs), as well as nuclear hybrid energy systems, including hydrogen, is advancing quickly, with several designs expected to be commercially deployed within 5 to 10 years, which could displace an additional 15 gigatonnes of carbon dioxide emissions by 2050.
  - **Policies should be technology-neutral, structured to incentivise desired outcomes such as emissions reductions and security of energy supply**. This includes taxonomies, as well as criteria for access to climate finance (e.g. the Green Climate Fund), development finance (e.g. multilateral development banks such as the World Bank and others), and Environmental Social and Governance (ESG) finance. Metrics should be applied consistently with similar levels of scrutiny across technology options, to allow technologies to compete on equal footing. In this way, efficiency is best achieved with technology-neutral policies and criteria.

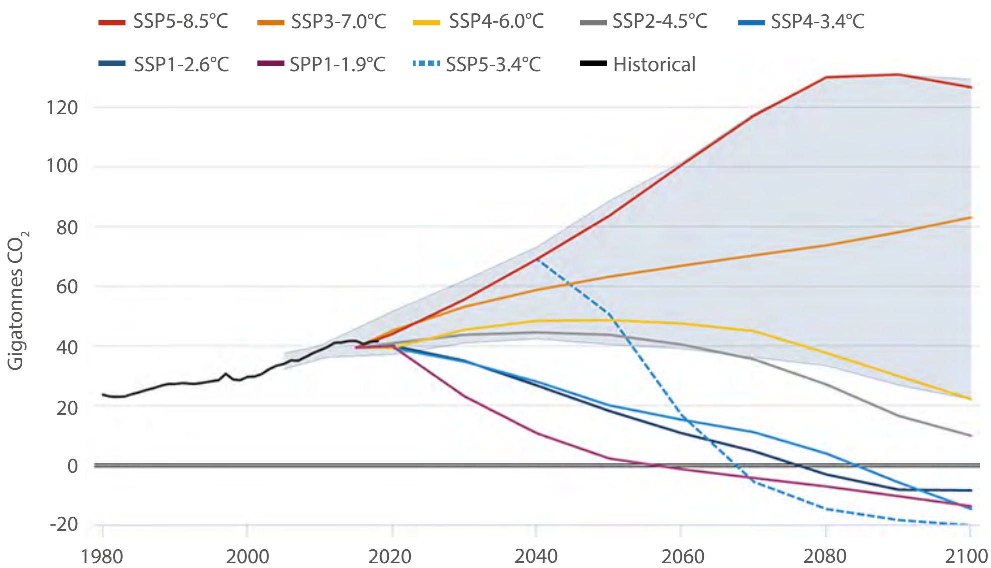
Meeting climate change targets: The role of nuclear energy

Global action is urgently needed

Leaders and governments around the world have identified the climate crisis as one of the defining challenges for this generation and an existential threat (US Department of Defense, 2021; 2021a). International organisations have found climate change has the potential to threaten the peace and security of people, as well as the environment, nature, and economy (UN, 2009; OECD, 2016; OECD, 2017). The UN Intergovernmental Panel on Climate Change (IPCC) has further identified climate change as a threat to food security, which could lead to scarcity-driven conflicts, in addition to migration and refugee crises around the world (IPCC, 2018).

The latest United Nations Intergovernmental Panel on Climate Change (IPCC) report concludes that climate change is widespread, rapid and intensifying and calls for strong, rapid, and sustained reductions in greenhouse gas emissions (IPCC, 2021). Similarly, the International Energy Agency (IEA) has reported that the path to net zero emissions is "narrow" and will require massive deployment of all available clean energy technologies (IEA, 2020).

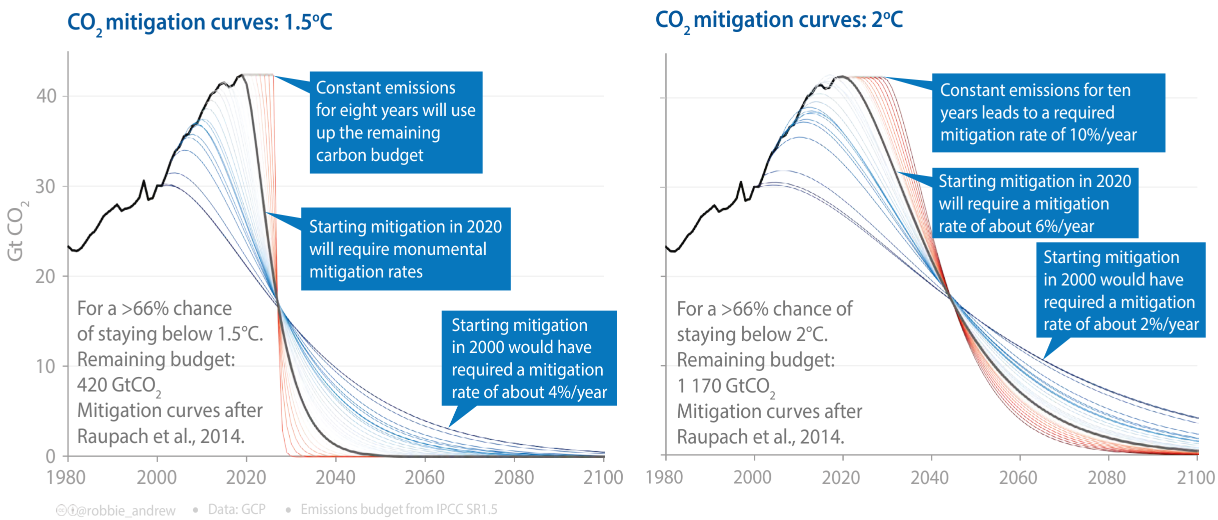
Figure 1. **Temperature outcomes for various emissions futures**



Source: Carbon Brief (2019).

The magnitude of the challenge should not be underestimated. In order to limit climate change to 1.5°C by the end of the century, the planet has a "carbon budget" of 420 gigatonnes of carbon dioxide emissions (Raupach et al., 2014), which represents the maximum quantity of carbon dioxide that can be emitted into the atmosphere while still keeping climate change to a maximum of 1.5°C. As illustrated in Figure 1, there is an implicit trade off between peaking early and ramping down emissions gradually; delaying peak emissions would necessitate increasingly rapid emissions reductions.

Figure 2. **Global carbon budgets for 1.5°C and 2°C scenarios**



Source: Andrew (2020).

While there exists some flexibility to peak early and ramp down gradual or peak later and ramp down more aggressively, it is generally understood that carbon dioxide emissions in 2030 will need to decline by approximately 45% compared to 2010 levels, before reaching net zero around 2050. In practical terms, and considering that overall carbon dioxide emissions increased between 2010 and 2020 by more than 5%, emissions would need to decline by more than 6% per annum in the current decade. Nevertheless, global carbon dioxide emissions are expected to grow to an all-time high in 2022-23 as economies recover from the COVID-19 pandemic. However, as highlighted by the synthesis report from UN Climate Change, the world is clearly not on track. Based on the plans issued by governments under the auspices of the Paris Agreement, emission will rise 16% by 2030. The window for action is rapidly narrowing. If carbon were emissions only remain constant, the entire carbon budget would be consumed within eight years.

Electrification of various sectors, including transportation and heavy industry, is expected to be a key strategy in global decarbonisation, which will create significant growth in demand for electricity generation and bring transformative changes to our economies. Even with improvements to demand-side management and energy efficiency, the demand for electricity demand will increase at an ever faster rate in the coming decades. The power sector is the largest carbon dioxide emitter making up more than 40% of the global emissions, followed by transport and industry sectors representing each around 25% (IEA, 2021a). Some models forecast total final electricity demand will increase by a factor of 2.5 between 2020 and 2050 while energy efficiency improves at a rate of 4% per year (IEA, 2021c).

At its core, the Paris Agreement is an agreement about transforming the world's energy mix. Having come into force 4 November 2016, the historic Paris Agreement has three aims:

1. Limiting the increase in global average temperature well below 2°C with additional efforts to limit warming to 1.5°C above pre-industrial levels;
2. Fostering adaptation and resilience efforts; and
3. Ensuring climate financing.

It is noteworthy that, despite its status as an historic agreement moving the world in the right direction vis-à-vis climate change mitigation and adaptation, the Paris Agreement and its associated national determined contributions are insufficient; humanity must do much more to achieve the stated objective of the 2°C scenario.

The need to mobilise all low-carbon energy technologies

Fundamentally, there is no sustainable level of emissions if the 2°C scenario is to be realised. Constrained by the world's carbon budget, carbon emissions must peak within the next few years and go to zero by 2100 (or sooner). This will require policy changes around the world as well as massive investments in innovation, infrastructure, and deployment of non-emitting energy resources. More specifically, electricity grids must be decarbonised; vehicle fleets must be electrified or transitioned to non-emitting fuels; and a range of industrial sectors (e.g. off-grid mining, buildings, chemicals, iron and steel, cement, oil and gas) must be transformed as well.

Whatever else might be said about the efforts undertaken thus far, they are on track to far exceed the targets arising from the 2°C scenario. It is clear that a shift in direction will be required if countries' stated objectives are to be met.

As highlighted by NEA studies such as *The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*, countries face unique and distinct options and challenges in their efforts to achieve optimum energy portfolios (NEA, 2019). There is no commonly applicable solution for all countries. The best energy mix and energy strategy depends on, inter alia, a country's natural endowments, state of economic development, technological capabilities, human capital, stability, legal and regulatory frameworks, as well as culture, values, and priorities.

Many countries are committing to reach net zero emissions by 2050. It has yet to be seen, however, whether countries have the technologies and political will to achieve this ambitious target of net zero by 2050. It is clear that a serious effort to do so would require massive investments in and deployment of all non-emitting energy solutions, including renewable energy, nuclear energy, and carbon capture, utilisation and storage (CCUS), in addition to energy storage, energy efficiency, and demand-side management, among other measures.

There is no "silver bullet", no perfect solution to the complex and urgent challenge of climate change mitigation. All non-emitting energy options offer benefits but face limitations and challenges.

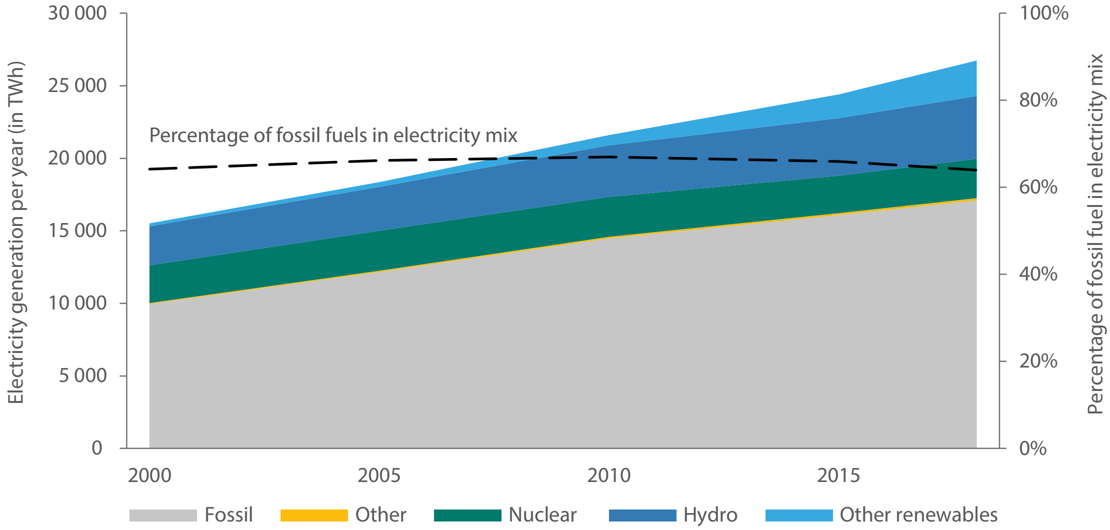
While hydroelectricity and nuclear energy currently account for approximately 16% and 10% of the world's electricity supply, respectively, variable renewables (e.g. wind and solar) are the fastest growing segment of the clean energy market. Hydroelectricity is expected to continue to play an important role in providing baseload power; however, it is not a solution in many parts of the world that lack hydro potential. In theory, other non-emitting technologies, such as variable renewables, nuclear power, and CCUS, can be transferred and deployed in most jurisdictions around the world. In practice, the effectiveness and efficiency of variable renewable technologies (e.g. wind and solar) also varies by jurisdiction, but has great potential in many energy poor parts of the world (e.g. near to the equator for solar potential). Embarking nuclear nations face some barriers to entry, including the need to implement effective regulatory frameworks as nuclear is a strictly controlled sector; however, engagement with the international community – through the International Atomic Energy Agency (IAEA) with its milestones approach or bilaterally with experienced nuclear nations for capacity building – can facilitate successful outcomes.

Variable renewables generally benefit from strong public confidence in many parts of the world; however, the sun does not always shine and the wind does not always blow, and the variable (and often unpredictable) nature of these forms of power generation can create systems level challenges and grid instability, that translate into higher systems costs. Higher levels of variable renewables could be deployed more aggressively if they could be coupled with adequate energy storage capacities, dispatchable power, and baseload power. Storage and batteries, however, are not yet available at the scale that would be required to replace fossil energy with variable renewables and achieve zero global emissions by 2050.

Despite the massive capacity additions of variable renewables (mainly wind and solar power) over the last two decades, the relative share of fossil fuels in the electricity generation mix has barely changed (see Figure 3 below). In fact, the surge in variable renewable generation has primarily served to compensate for the decline of nuclear power output. In absolute terms, electricity generation from fossil fuels has also increased globally, driven in large part by increasing electricity demand in non-OECD countries.

As a result, global carbon emissions are far from being on track with the Paris Agreement. After two years of consecutive increases, carbon emission flattened at 33 gigatonnes of carbon dioxide in 2019. In 2020, carbon dioxide emissions experienced a major fall of 5% mainly due to a major global economic downturn during the COVID-19 pandemic. The fall in emissions in 2020 was not based on any structural changes in emission patterns. Accordingly, driven by post COVID-19 economic recovery, carbon emissions are expected to increase by 5% in 2021, regressing to levels prior to the pandemic (IEA, 2021b).

Figure 3. **Growth in electricity generation (2000-2018)**



Source: IEA (2021a).

CCUS may have a role to play, not only in reaching net zero emissions, but in exceeding this target to reach net negative emissions. There are several potential scenarios that could unfold, with countries taking steps to reach net zero emissions by 2050. In some possible scenarios, if countries do not reach peak emissions early enough, the world could exceed its carbon budget even if it reaches net zero by 2050. In this scenario, CCUS would be required to extract carbon from the atmosphere after it has been emitted (a model that is often referred to as negative emissions), reversing and mitigating some of the worst effects of climate change.

There is considerable uncertainty however in the readiness of CCUS technologies. CCUS technology readiness levels are low, with several projects presently ongoing to demonstrate the viability and scalability of CCUS. The IEA (2021c) has identified CCUS as one of the three key uncertainties in the pathway to net zero by 2050, along with behavioural changes and bioenergy.

Natural gas, as the least carbon intensive fossil fuel, may be a good fit in many jurisdictions in the short term, for gradually decarbonising the global energy mix; however, in order to go to zero emissions by 2100, natural gas will likely also need to be phased out (unless it can be paired with CCUS). Breakthroughs in renewables, energy storage, energy efficiency, as well as CCUS are needed. Equally importantly, however, the IEA anticipates that, in order to achieve the 2°C scenario, global installed nuclear energy capacity will need to double by 2050. This will require significant investments in life extension and refurbishment of existing nuclear reactors, as well as new builds of existing large-scale nuclear power technologies, as well as investments in small modular reactors (SMRs) and Generation IV technologies.

All credible models show that nuclear energy has an important role to play in global climate change mitigation efforts. In its 2019 report on nuclear energy – its first report on nuclear energy in over 20 years – the IEA found that nuclear has an important role to play in global efforts to meet Paris Agreement targets (IEA, 2019). Nuclear power plant retirements would significantly constrain global climate change mitigation efforts. Conversely, investments in nuclear energy life extensions and refurbishments of existing reactors, as well as new builds, would make it less expensive and more feasible to meet Paris Agreement targets.

Despite clear analyses from many sources, including the NEA, that point to the need for a massive, "all-the-above" approach that includes nuclear energy, many multinational efforts, financial institutions, and policy positions avoid nuclear energy. However, if countries do not invest in nuclear energy, the risks of failure to meet Paris targets will be significantly greater. The IEA, for example, estimates that it would cost the world an estimated USD 1.6 trillion more to meet Paris targets without nuclear energy (IEA, 2019). Ultimately, even this estimate may prove optimistic.

As countries work to optimise their energy mixes and strategies for reaching climate change mitigation targets, some opportunities and challenges will emerge for nuclear energy around the world.

Box 1: **Nuclear energy in pathways to net zero emissions by 2050**

As more and more countries commit to dramatically reduce emissions, many are seeking to understand the pathways that could lead the world from where it is today to net zero by 2050.

Pathways based on the world's carbon budget, emissions reductions targets and timelines, have been modelled and published by various organisations, such as the United Nations Economic Commission for Europe (UNECE) and the International Energy Agency (IEA), as well as other organisations, including the International Institute for Applied Systems Analysis (IIASA), Bloomberg New Energy Finance (BNEF), Shell and BP, among others, and many of these scenarios are taken into account in assessments by the United Nations Intergovernmental Panel on Climate Change (IPCC). In a special report published in 2018, the IPCC considered 90 pathways consistent with a 1.5°C scenario and 200 pathways consistent with a 2°C scenario – i.e. pathways with emissions reductions sufficient to limit average global warming to less than 1.5°C and 2°C respectively.

Despite the large numbers of published pathways, there continues to exist considerable uncertainty with respect to the feasibility – and the costs – of reaching net zero by 2050. In particular, many published pathways depend on energy technology innovations that have not yet been commercialised (or even demonstrated in some cases), such as widespread deployment of CCUS technologies and an integrated hydrogen economy.

Table 1. **Samples of ambitious and aspirational pathways to net zero**

Organisation	Scenario	Parameter	2020	2050	Growth rate (2020-50)
IIASA (2021)	Divergent Net Zero Scenario (1.5°C)	Cost of carbon (USD per tCO_2)	0	1 647	-
		Wind (in GWe)	600	9 371	**1 461%**
		Solar (in GWe)	620	11 428	**1 743%**
IEA (2021c)	Net Zero Scenario (1.5°C)	Hydrogen (MtH_2)	90	530	**490%**
		CCUS ($GtCO_2$)	<0.1	7.6	-
		Energy intensity (MJ per USD)	4.6	1.7	**-63%**
Bloomberg NEF (2021)	New Energy Outlook Green Scenario (1.5°C)	Wind (in GWe)	603	25 000	**4 045%**
		Solar (in GWe)	623	20 000	**3 110%**
		Batteries (in TWh)	<0.1	7.7	-

It is notable, however, that none of the pathways project particularly aspirational scenarios for nuclear innovation. In other words, all published pathways include levels of nuclear energy deployment based on currently available commercial technologies. Some are ambitious in the extent of the deployment – for example, BNEF envisages up to 7 400 gigawatts of installed capacity by 2050 – but none depend on nuclear innovation that has not yet been realised. This represents a significant gap in current pathways publications, as the potential exists for near-term and medium-term nuclear energy innovation to play a significantly larger role in decarbonisation strategies.

Table 2. **Nuclear in emissions reduction pathways**

Organisation	Scenario	Publication year	Climate target	Role of nuclear technologies		Description	Role of nuclear energy by 2050	
				Large Generation III	Nuclear Innovation		Capacity (GW)	Nuclear growth (2020-50)
IAEA (2021b)	High Scenario	2021	2°C	Included	Not included	Conservative projections based on current plans and industry announcements.	792	98%
IEA (2021c)	Net Zero Scenario (NZE)	2021	1.5°C	Included	Not included in the quantitative model, although the potential of HTGR and nuclear heat are acknowledged in the report narrative	Conservative nuclear capacity estimates. NZE projects 100 gigawatts more nuclear energy than the IEA sustainable development scenario.	812	103%
Shell (2021)	Sky 1.5 Scenario	2021	1.5°C	Included	Not specified	Ambitious estimates based on massive investments to boost economic recovery and build resilient energy systems.	1 043	160%
IIASA (2021)	Divergent Net Zero Scenario	2021	1.5°C	Included	Not specified	Ambitious projections required to compensate for delayed actions and divergent climate policies.	1 232	208%
Bloomberg NEF (2021)	New Energy Outlook Red Scenario	2021	1.5°C	Included	Explicit focus on SMRs and nuclear hydrogen	Highly ambitious nuclear pathway with large-scale deployment of nuclear innovation.	7 080	1670%

Through discussions with the organisations publishing pathways and their modelling teams, it is clear that the reasons nuclear innovation does not feature more prominently alongside other energy innovations are unrelated to the potential of nuclear innovation. Many pathways have shied away from including nuclear innovation because of a lack of specialised expertise in nuclear technologies among the modelling teams. This represents a significant gap where the NEA could play a role in raising awareness and providing authoritative quantitative assessments of the potential of future nuclear innovation to contribute to ambitious climate change pathways.

Despite the uncertainties about energy innovations and costs, some key conclusions from analysis of the multitude of pathways are clear:

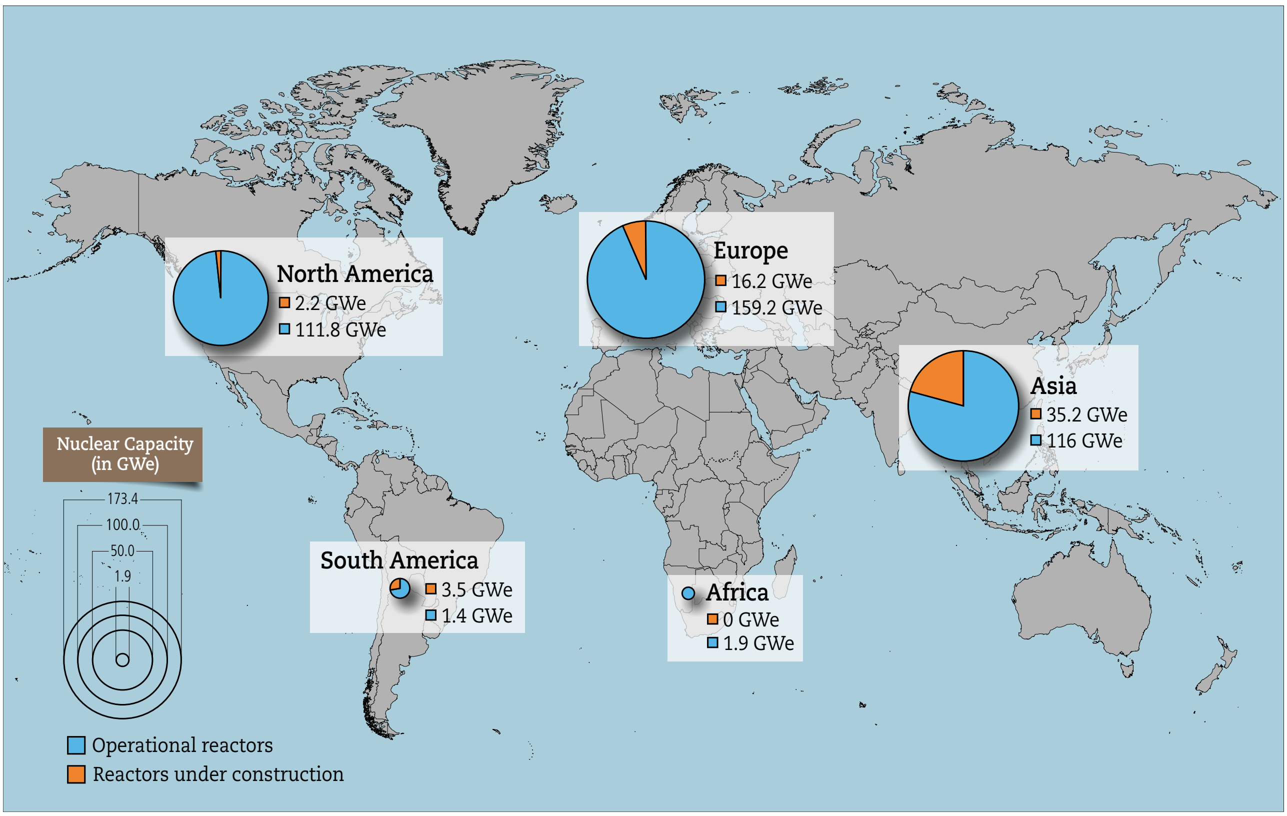
- Firstly, all pathways present significant challenges for the energy sector from a technological, economic and policy perspective. Reaching net zero will require a rapid and far-reaching transformation of the energy sector, which will require massive investments in energy innovation and progress in a number of energy technologies under development.
- Secondly, all pathways require global installed nuclear capacity to grow significantly, often more than doubling from current levels by 2050. Four IPCC illustrative pathways (IPCC, 2018) depict global installed nuclear capacity growing by a factor between 2 and 6 between 2010 and 2050, reaching as much as 13 176 TWh by 2050, up from 2 630 TWh in 2010.

The role of nuclear energy

Nuclear energy today

There are 444 nuclear power reactors currently in operation worldwide providing 394 gigawatts of electricity capacity, plus approximately 50 more under construction to provide an additional 55 gigawatts of capacity. More than 100 additional reactors are planned. In 2018, nuclear energy supplied approximately 2 563 TWh of electricity worldwide, 2 101 TWh in NEA member countries (NEA, 2021; WNA, 2020).

Figure 4. **Global nuclear capacity by continent (2021)**



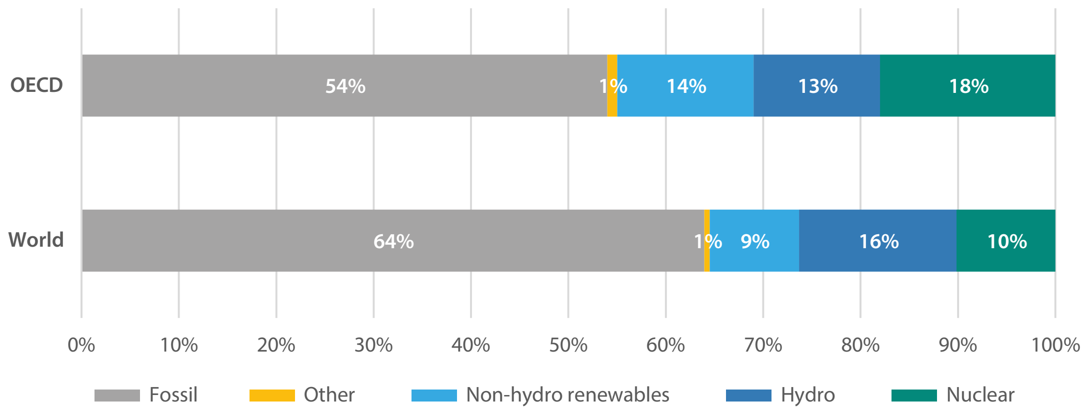
Existing nuclear capacity displaces 1.6 gigatonnes of carbon dioxide emissions annually and has prevented displaced 66 gigatonnes of carbon dioxide since 1971, the equivalent of two years of global emissions (NEA, 2021d).

Table 3. **Global installed nuclear energy capacity by continent (2021)**

444	30	394	66
nuclear reactors in operation globally	countries with nuclear reactors	gigawatts global installed nuclear capacity	gigatonnes of CO_2 cumulative emissions avoided since 1971

Nuclear energy supplies approximately 10% of the world's electricity and is the world's fourth largest source of electricity, following coal, gas and hydroelectricity, which supply approximately 38%, 23%, and 16% of the world's electricity, respectively (WNA 2020). Nuclear energy, therefore, is the world's second largest source of non-emitting electricity, following hydroelectricity, and the largest source of non-emitting electricity in the group of OECD countries (Figure 5). In regions that are not rich in hydroelectric potential, nuclear is generally the most significant non-emitting option for electricity generation.

Figure 5. **OECD and World Electricity Mixes (2018)**



Source: Based on IEA (2021a).

The United States Energy Information Administration's *International Energy Outlook* projects that global nuclear capacity will continue to grow at a rate of 1.5% per year through 2040 (EIA, 2017). The geopolitical landscape for nuclear energy is transforming in important ways. While some NEA countries do not include nuclear in their future plans (e.g. Germany) or face questions about the future of current installed nuclear capacity (e.g. Japan, United States), growth in nuclear energy is driven principally by non-NEA countries (e.g. China and India). Accordingly, whereas over 80% of global installed nuclear capacity has been within OECD countries, by mid-century, this percentage could fall below 50% (EIA 2017), with significant geopolitical implications, including global shifts in high-value, strategic industrial capacity, human resource capabilities, policy influence, and the development of vital technologies.

While conditions exist to support growth in global nuclear energy development and deployment, the nuclear energy sector faces many challenges. Global energy demand is expected to continue growing, driven primarily by China, India, and South East Asia. Concerns over climate change are rising and will drive demand for non-emitting energy. However, uncertainties in global resource markets, as well as increases in resource nationalism and protectionism, are having chilling effects on global trade in uranium and nuclear technologies, and geopolitical instability is giving rise to non-proliferation concerns. Moreover, lack of key infrastructure and enabling frameworks creates barriers to access in key markets for new nuclear energy.

An increasingly networked global civil society has high expectations for transparency, accountability, social engagement, environmental protection, safety (post-Fukushima), and benefits sharing. Civil society also has high expectations for the potential of renewables, storage, and demand-side management to fully address climate change and energy security concerns.

Nuclear energy is often excluded from public and political discourse, creating significant challenges for the nuclear sector. Even countries that include nuclear in their existing and future energy plans often remain silent on the role of nuclear in international clean energy and climate change fora. This dynamic is deeply problematic. Nuclear energy must be included alongside other options in discussions about energy transition in order to maintain the integrity and evidence base of the policy dialogue. While energy policy makers may take different values-based decisions on the role of nuclear energy in their respective national contexts, the analyses and assessments that inform policy debates must be complete and evidence-based. Including all options in the analyses is necessary to ensure that the complex trade offs between options can be accurately understood and contemplated.

Box 2: **Flexible nuclear energy**

Markets are signalling demand for flexible power generating options to support the low-carbon energy transition. A recent report under the Clean Energy Ministerial's nuclear energy initiative considered the potential of nuclear power to provide much needed flexibility. The key findings of that report are presented in this box.

The NICE Future Initiative was launched during the 9th Clean Energy Ministerial (CEM9) in 2018. The main purpose of NICE Future Initiative is to explore innovative applications of existing and advanced nuclear power with a strong focus of nuclear flexibility. More recently, the Flexible Nuclear Campaign has been initiated to analyse in more detail the value of nuclear flexibility in electricity systems with high shares of VRE.

One of the first deliverables of the Flexible Nuclear Campaign was the publication of *Flexible Nuclear Energy for Clean Energy Systems*, released in September 2020 (NREL, 2020). The study gathers extensive techno-economic evidence on the current and potential future roles of nuclear power in providing flexibility to meet energy demands.

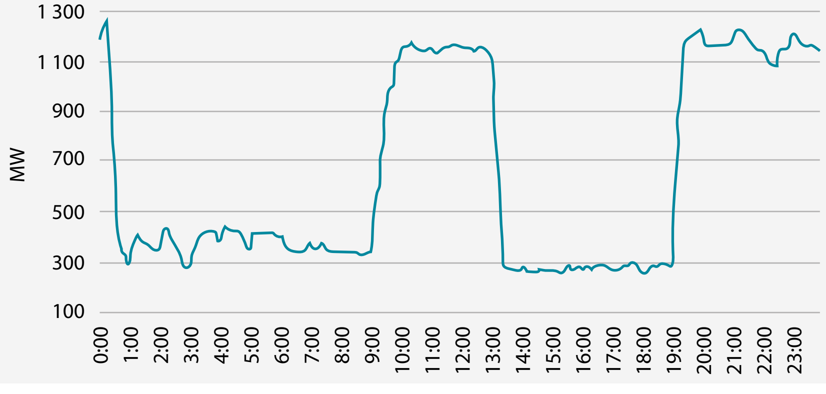
In the study, nuclear flexibility is defined as:

> "The ability of nuclear energy generation to economically provide energy services at the time and location they are needed by end-users. These energy services can include both electric and nonelectric applications utilizing both traditional and advanced nuclear power plants and integrated systems" (NREL, 2020).

While nuclear flexibility will be ultimately bounded by the characteristics of the electricity system and its technologies, three high-level trends can be identified:

- **There is already an established body of knowledge surrounding flexible operation of existing nuclear power plants**: In most regions, especially where the share of nuclear in the electricity mix is low, nuclear reactor are operated in baseload mode. However, countries like France and Germany, have extensive experience in operating nuclear reactors in load-following mode varying their power up to 80% twice per day (Figure 6). Nuclear reactors also provide key services for the stability of the electricity system such as inertia, short-circuit power and frequency control.
- **Innovation could increase the flexibility of nuclear systems with advanced systems opening the door to novel applications**: Existing nuclear systems can be retrofitted to accommodate higher manoeuvrability levels but also to diversify their energy products. The latter allows for nuclear reactor to be operated continuously at full rated power while switching to heat or electricity depending on market conditions. Demonstration projects are planned in several NEA countries to use the part of the electricity output to feed electrolysers for hydrogen production.
- **Nuclear flexibility enables the integration of higher shares of VRE and fosters nuclear development**: to be technically and economically feasible electricity systems with high shares of variable renewables require a residual system sufficiently flexible to accommodate the variable out at a reasonable cost while limiting the decline in market value. Hybrid/integrated energy systems emerge as an opportunity to provide high levels of system flexibility while fostering decarbonisation across sectors.

Figure 6. **Example of power variations over 1 day, Golfech 2 nuclear power plant, 1 300 MW**

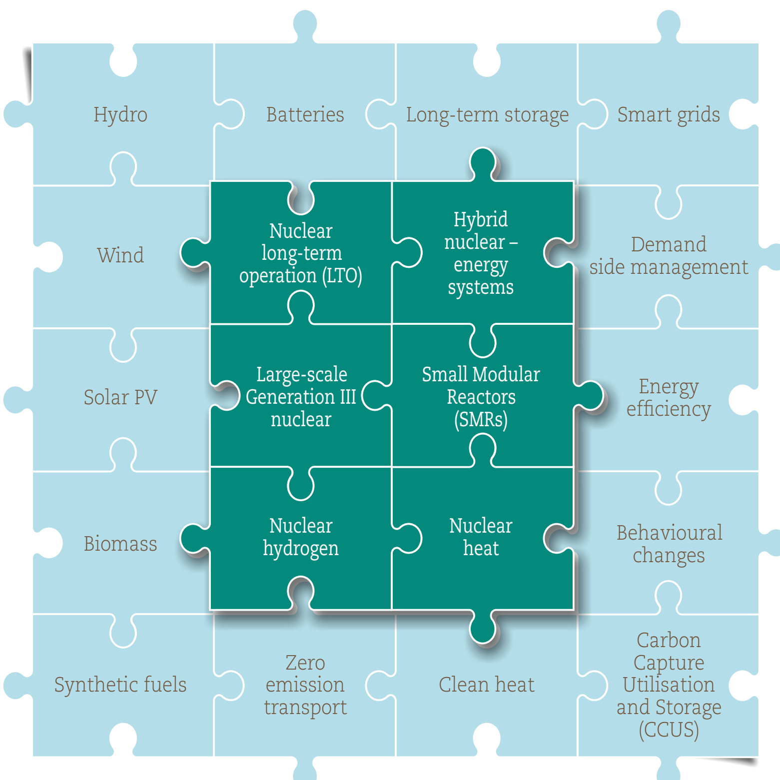


In order to take advantage of the full potential of nuclear flexibility, innovation and demonstration projects are required in the current decade. For power plants that are otherwise used in baseload, flexibility lowers the load factor and increases average plant level costs. Accordingly, the economic implications also need to be attractive, requiring in particular market frameworks that adequately reward the value of flexible nuclear energy.

The future of nuclear energy

The nuclear sector can support climate change mitigation efforts in a variety of ways. Existing global installed nuclear capacity is already playing a role and long-term operation can enable the existing fleet to continue making a contribution for decades to come. There is also significant potential for large-scale Generation III nuclear new builds to provide non-emitting electricity in existing and embarking nuclear power jurisdictions. In particular, these projects could replace coal power around the world. A wave of near-term and medium-term nuclear innovation has the potential to open up new opportunities with Generation IV and small modular reactors (SMRs), as well as nuclear hybrid energy systems, reaching into new markets and applications including (but not necessarily limited to) sector coupling, combined heat and power (cogeneration) for heavy industry and resource extraction, hydrogen and synthetic fuel production, desalination, and off-grid applications.

Figure 7. **Nuclear technologies and applications in future low-carbon energy systems**



Long-term operation of nuclear power plants

As the name implies, long-term operation of nuclear power plants is generally defined as operation, justified by a comprehensive safety assessment that goes beyond a previously conceived time frame, which typically corresponded to so-called “initial design assumptions”. These initial design assumptions, however, do not represent a technical constraint inhibiting longer operating times and should not be confounded with the remaining, useful life of the facilities, which can be periodically re-evaluated taking into account the actual plant conditions and the latest available knowledge. In almost all cases, the useful life of facilities is significantly longer than the originally assumed time frame. In the United States, for example, nuclear plants have been approved for operations up to 80 years.

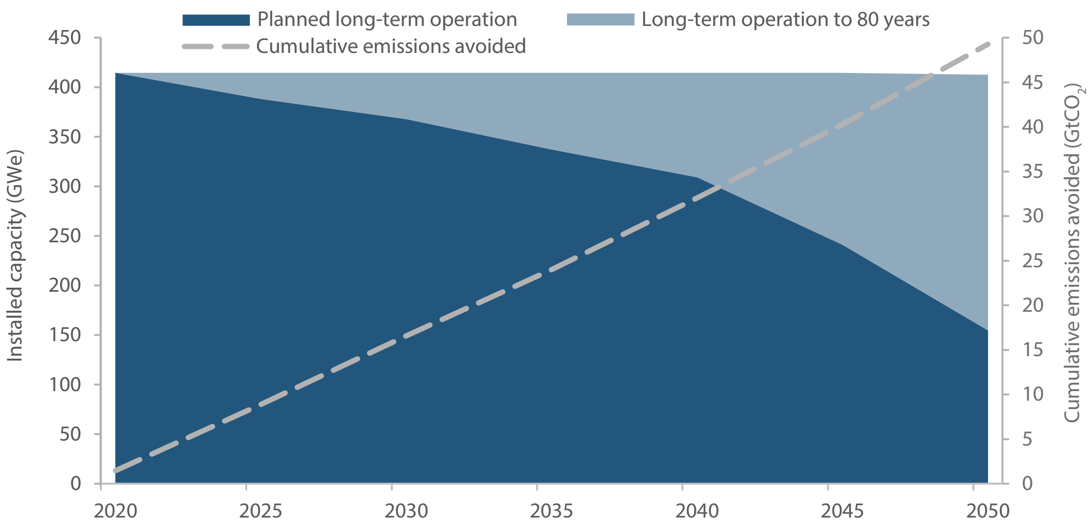
Presently, the average age of nuclear power plants in OECD countries is 36 years. The technical potential exists in most cases for long-term operation for several more decades, subject to refurbishments and licence extensions as required. Most component parts of nuclear power plants can be maintained, refurbished or replaced, with the notable exceptions of pressure vessels and concrete containment buildings that are already long-lasting and can support long-term operation, supported by appropriate ageing management programmes.

The potential and limitations of long-term operation are considered in greater detail in the 2021 NEA report *Long-Term Operation of Nuclear Power Plants and Decarbonisation Strategies*. The report builds on the earlier finding by the NEA and IEA that long-term operation are one of the most cost-competitive sources of low-carbon electricity (IEA/NEA, 2020). Decisions to pursue licence extensions and long-term operation are often characterised by less uncertainty and less risk than decisions regarding new builds (NEA, 2021b).

While there exists significant potential for long-term operation to contribute to climate mitigation efforts, some countries are facing policy challenges and early closures of nuclear reactors are taking place. Beyond technical feasibility, there are several other enabling conditions required for long-term operation, including policy and market conditions. Some OECD countries are retiring nuclear power plants that could otherwise be strong candidates for long-term operation, due to policy decisions such as phase-out mandates or electricity market measures that promote variable renewables and often also under-value dispatchability, capacity, and other system-level benefits of nuclear power plants.

With enabling policies that allow nuclear power plants to compete on a level playing field with other non-emitting power generation options, long-term operation could play a growing role in the coming decades as a key pillar of decarbonisation strategies. The long-term operation of existing reactors could save up to 49 gigatonnes of cumulative carbon emissions between 2020 and 2050.

Figure 8. **Long-term operation – installed capacity and cumulative emissions avoided (2020-2050)**



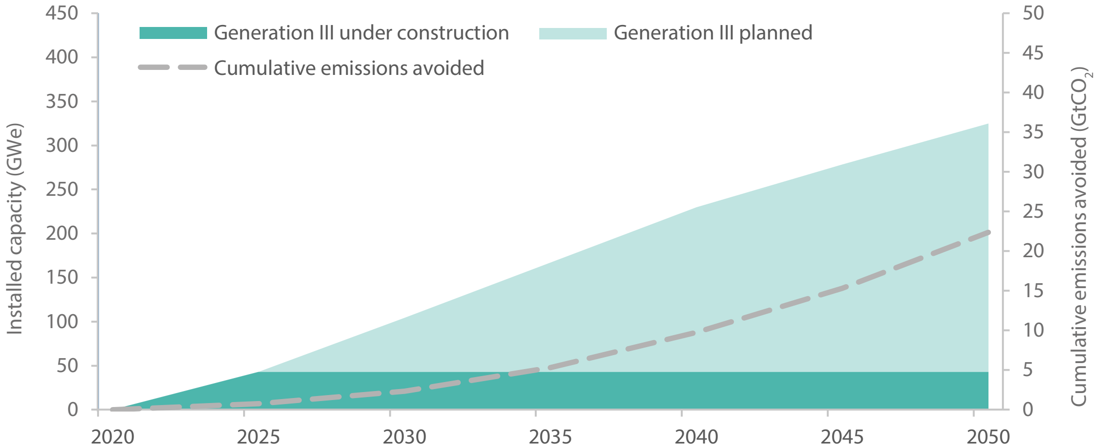
Note: It is assumed that nuclear power (12 gCO_2eq/kWh) is displaced by gas with a carbon footprint of 490 gCO_2eq/kWh (Bruckner, 2014). By 2050, 25% of nuclear reactors are used for nuclear heat applications, also displacing gas. By 2050, nuclear reactors operate with a 90% availability factors with 60% of the power used to supply electricity and 30% to supply hydrogen. Hydrogen produced with nuclear power will displace steam methane reforming (10 kg CO_2 per kg of H_2).

New builds of large Generation III nuclear technologies

At the end of 2020, 55 gigawatts of new nuclear capacity in the form of large-scale Generation III reactors were under construction around the world (IAEA, 2021) driven largely by new builds outside the current OECD membership. Approximately 25% of nuclear new builds are in China, followed by 13% in India.

Taken together, large-scale Generation III reactors that are under construction and planned are expected to reach over 300 gigawatts of installed capacity by 2050, avoiding 23 gigatonnes of cumulative carbon emissions between 2020 and 2050.

Figure 9. **Generation III new builds – installed capacity and cumulative emissions avoided (2020-2050)**



Note: It is assumed that nuclear power (12 gCO_2eq/kWh) is displaced by gas with a carbon footprint of 490 gCO_2eq/kWh (Bruckner, 2014). Planned construction based on NEA/IEA Tracking Clean Energy Progress 2021 – nuclear chapter. By 2050, 25% of nuclear reactors are used for nuclear heat applications, also displacing gas. By 2050, nuclear reactors operate with a 90% availability factors with 60% of the power used to supply electricity and 30% to supply hydrogen. Hydrogen produced with nuclear power will displace steam methane reforming (10 kg CO_2 per kg of H_2).

Small modular reactors (SMRs)

Considering the magnitude of global emissions reduction targets, both long-term operation of existing nuclear power plants as well as new builds of Generation III gigawatt-scale reactors have important roles to play. In addition, a wave of innovation in small modular reactors (SMRs) could unlock even further emissions reductions by reaching into hard-to-abate parts of the economy, providing off-grid options, and options for sites that do not require (or cannot support) gigawatt-scale power generation.

SMRs are generally defined as nuclear reactors with power output less than 300 megawatts electric (MWe), with some SMRs as small as 1-10 MWe that are often referred to as micro-SMRs (or MMRs).

Table 4. **SMRs – definition**

Small	Smaller power output and smaller physical size than conventional gigawatt-scale nuclear reactors. SMRs are smaller than 300 megawatts electric.
Modular	Modular manufacturing, factory production, portable, scalable deployment.
Reactor	Nuclear fission reaction creates heat that can be used directly or to generate electricity.

As a class of reactors, SMRs are defined by their smaller size, but there exists considerable variety within this class of reactors; they vary by power output, temperature output, technology, and fuel cycle. Accordingly, they also vary in technology readiness level (TRL) and regulatory readiness level (RRL). Some SMR technologies are already demonstrated (at lab and commercial scales), while others are still in research and development. Timelines for deployment vary based on technology and regulatory readiness levels, with some designs expected to be demonstrated and commercialised before 2030 and others to follow later in the 2030s.

Table 5. **SMRs – key technical features**

Power	SMRs vary in size from 1 to 300 megawatts electric.
Temperature	Near-term and medium-term SMRs generate a range of temperatures from 285°C to 850°C. Some designs may generate higher temperatures, up to or over 1 000°C in the future.
Technology	Some SMRs are based on Generation III and light water reactor technologies; others are based on Generation IV and advanced reactor technologies.
Fuel Cycle	Some SMRs are based on a once-through fuel cycle; others seek to close the fuel cycle by recycling waste streams to produce new useful fuel and minimise waste streams requiring long-term management and disposal.

The 2021 NEA report *Small Modular Reactors: Challenges and Opportunities* offers an overview of recent progress with the development and deployment of SMRs. The report discusses the key economic drivers of this innovative nuclear technology and highlights market opportunities for SMRs to support decarbonisation strategies, complement variable renewables as well as facilitate access to nuclear energy in new sectors and regions. The report also emphasises the need to review regulatory and legal frameworks and suggests grouping SMRs into different categories to support these policy changes. Finally, the report stresses the role of government support and international collaboration to enable large-scale SMR deployment.

SMR designs can be classified in a number of ways. The NEA suggests five categories: single-unit light water reactor (LWR) SMRs; multi-modular LWR-SMRs; mobile and transportable SMRs (including floating SMRs); Generation IV SMRs; and micro-modular reactors (less than 10 MWe) (NEA, 2021a).

Table 6. **SMRs – reactor types**

Single-unit LWR-SMRs	LWR-SMRs use of well-established LWR technology and fuels to provide stand-alone units that may replace small fossil-fuel units or be deployed as distributed generation.
Multi-module LWR-SMRs	Multi-module LWR-SMRs also use LWR technology, and may be either operated as a replacement for mid-size baseload capacity or in a distributed generation framework, depending upon generating capacity.
Mobile and transportable SMRs	Mobile and transportable SMRs currently apply LWR technology and are intended to be easily moved from location to location. Floating reactors are included in this category.
Generation IV SMRs	Generation IV SMRs apply advanced, non-LWR technologies and include many of the concepts that have been investigated by the Generation IV International Forum (GIF).
Micro-modular reactors (MMRs)	MMRs represent designs of less than 10 MWe of capacity, often capable of semi-autonomous operation and with improved transportability relative to the larger SMRs. These technologies are typically not LWR-based and apply a wide range of technological approaches, including Generation IV technologies. MMRs are principally intended for off-grid operation in remote locations where they are expected to be competitive with prevalent sources of electricity.

Source: NEA, 2021.

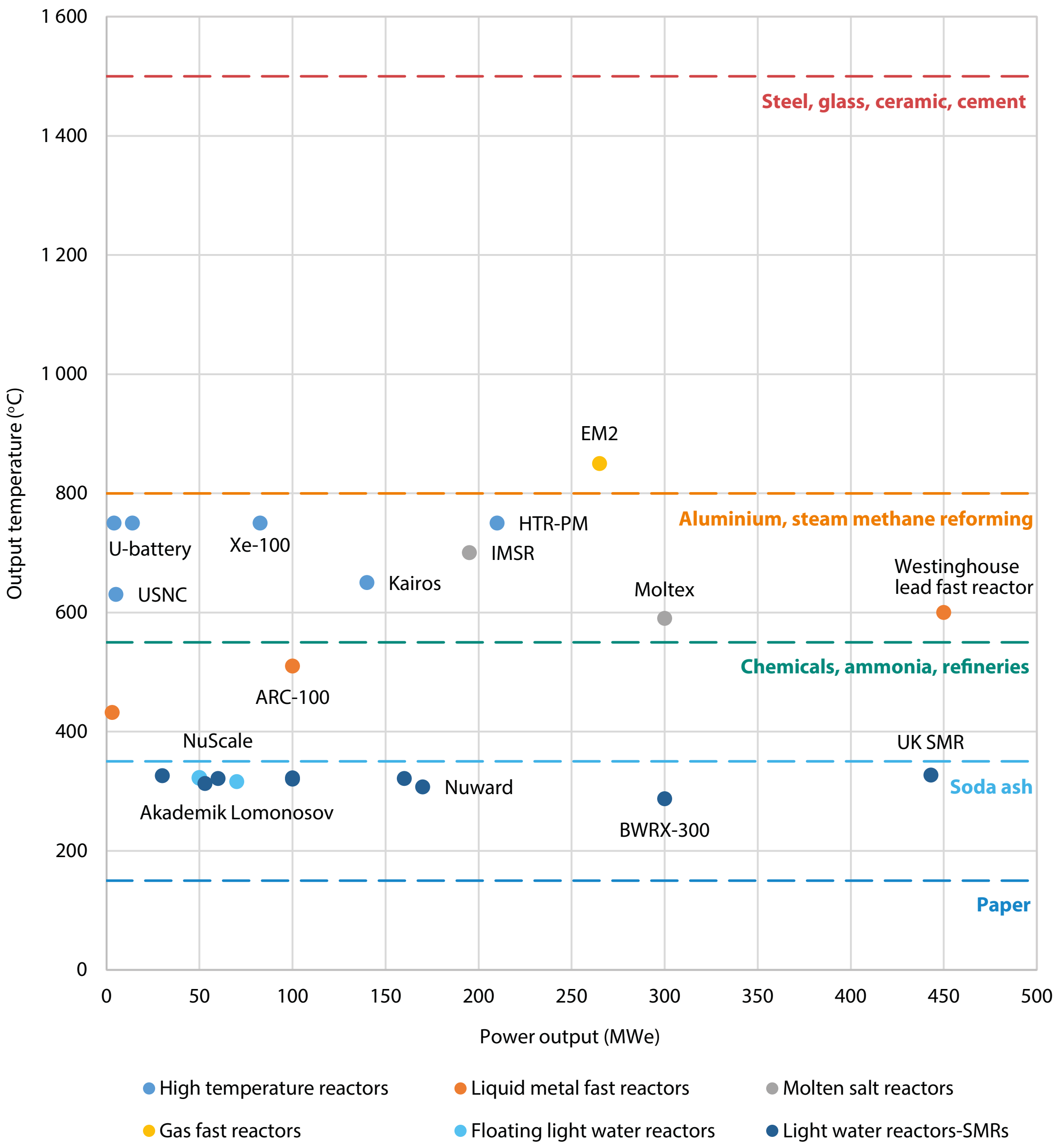
SMRs bring a number of unique design features that support both the safety case and economics of these innovative reactors. This includes integral designs that contribute to a robust inherent safety case, low core inventories to reduce the need for emergency planning zones, improved modularisation and manufacturability that would transform nuclear new builds delivery models, and enhanced flexibility for nuclear energy to further support variable renewables integration in the electricity mix.

Dozens of SMR designs are under development in countries around the world. The designs under development seek to provide different value propositions, with a variety of sizes and temperatures intended for different applications, as well as other features and benefits including, for example, simplified and enhanced safety, proliferation resistance, modular manufacturing, scalability, and even portability in some cases.

The variety of sizes and temperatures creates opportunities for SMRs to be deployed for a wide range of new applications, but competition is fierce as the global market is not expected to support all of the designs presently under development. A small number of different types of reactor concepts, providing different features (e.g. different sizes, temperatures, fuel cycles) could provide the flexibility to meet global requirements across a range of applications. Fleet deployment is expected with some potential for blended fleets that incorporate complementary types of reactor concepts. Various market and non-market forces will continue to advance winning technologies while others will fall behind. Beyond technical feasibility, winning SMR technologies will require regulatory approvals, financing, sites, operators, supply chains, customers, and public confidence.

Cost competitiveness of SMRs will depend on several factors. Modularisation is planned to drive new delivery models, with factory production expected to drive down unit costs through economies of series. The price of carbon and regulatory costs will also be key drivers of the economics of SMRs.

Figure 10. **SMRs – ranges of sizes and temperatures for heat applications**



Source: Analysis based on IAEA (2020).

While the pace of SMRs deployment is still subject to a number of uncertainties, it is clear from existing market outlook studies (e.g. NEA, Canada's SMR Roadmap, NNL, McKinsey & Company) that these reactors could see a rapidly increasing rate of construction in net zero pathways, with several

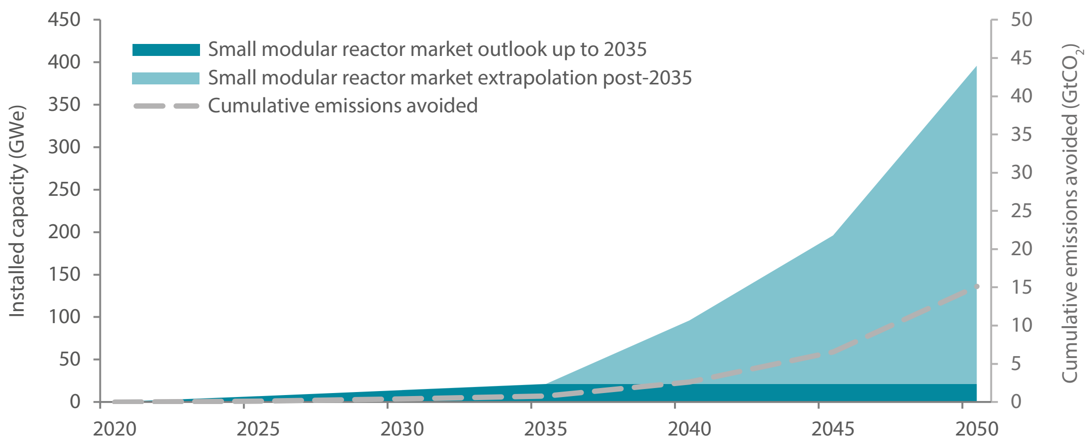
SMR designs expected to be commercially deployed within 5 to 10 years and ready to contribute to near-term and medium-term emissions reductions.

Up to 2035, the NEA estimates that the global SMR market could reach 21 gigawatts (NEA, 2016). Afterwards, a rapid increase in build rate can be envisaged with construction between 50 and 150 gigawatts per year considered by McKinsey & Company (2018). Assuming a build rate that reaches 75 gigawatts per year by 2050, up to 375 gigawatts of installed capacity would be built over the next three decades. This would translate into 15 gigatonnes of cumulative CO_2 emissions avoided.

Table 7. **SMRs – range of applications**

On-grid	Larger SMRs, in the range of 200-300 megawatts electric, are designed primarily for on-grid power generation, suitable for smaller grids that cannot support gigawatt-scale reactors, or in contexts where near-term growth in demand is not expected to warrant deployment of gigawatt-scale reactors. This size of SMRs is also especially well-suited to coal power plant replacement, where existing balance of plant and local infrastructure can be leveraged and reused to drive down plant replacement costs.
Off-grid	Several smaller SMRs, including micro-SMRs as small as 1 to 10 megawatts electric, are under development for off-grid applications, including as an alternative to diesel generators in remote communities and at resource extraction sites. In these contexts, SMRs may be used to provide power as well as heat for various purposes such as district heating, greenhouse heating, and mine-shaft heating, among other low heat applications. Micro-SMRs, in particular, create opportunities for distributed generation and site energy independence with potential applications for various types of sites that require greater energy security than the local grid offers including, for example, military bases, critical research campuses, and edge-of-grid or end-of-pipeline industrial sites, among others.
Heat	Many SMR designs, both small and large, will operate at higher temperatures, creating opportunities for deep decarbonisation of hard-to-abate portions of the economy. High temperature SMRs, or high temperature nuclear energy more broadly, could create the first real non-emitting alternative to fossil fuel cogeneration by offering combined heat and power solutions for industrial customers. Interest in this application is high, but success will require more than just technical feasibility. The size of the market for high temperature SMRs will depend on cost competitiveness (albeit in the presence of carbon prices and other policies to curb emissions), which will need to be proven, as well as alignment of other requirements, such as synchronicity of industrial project planning timelines with SMR deployment timelines.
Marine merchant shipping	Some SMRs are under development with the aim of providing a non-emitting alternative for marine merchant shipping propulsion representing, in effect, a civilian version of nuclear submarines and nuclear ice breakers that have been operating for several decades. Successful deployment of SMRs for marine merchant shipping could yield significant emissions reductions as shipping remains a very hard-to-abate industrial sector.

Figure 11. **SMR – installed capacity and cumulative emissions avoided (2020-2050)**



Note: It is assumed that nuclear power (12 g CO_2eq/kWh) is displaced by gas with a carbon footprint of 490 g CO_2eq/kWh (Bruckner, 2014). SMR 2035 market outlook based on NEA (2016). Extrapolation post-2035 based on SMR build rate envisaged by McKinsey & Company (2018) "Nuclear deep decarbonization scenario". By 2050, 25% of nuclear reactors are used for nuclear heat applications, also displacing gas. By 2050, nuclear reactors operate with a 90% availability factors with 60% of the power used to supply electricity and 30% to supply hydrogen. Hydrogen produced with nuclear power will displace steam methane reforming (10 kg CO_2 per kg of H_2).

Box 3: **Generation IV reactors**

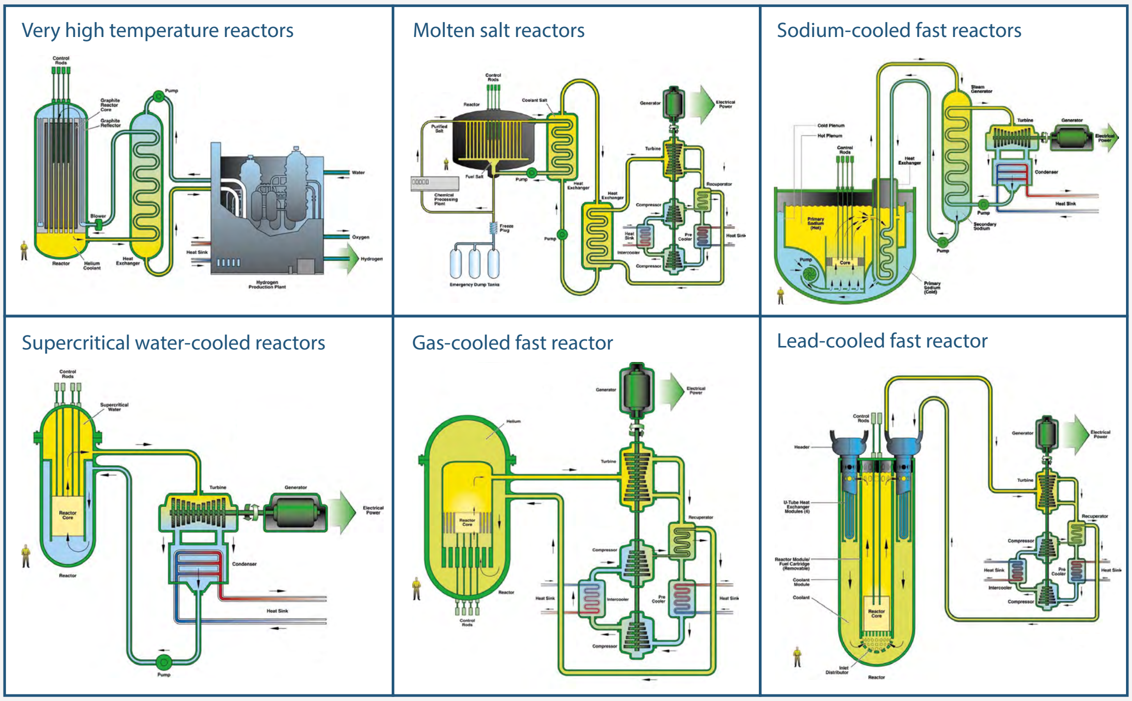
Generation IV reactors are advanced reactors that aim to take advantage of high-temperature coolants such as helium, liquid metals, liquid salts, or supercritical water. This additional design flexibility allows for up to a 40% increase in thermal efficiency, while also opening the option of industrial heat applications that can displace substantial fossil fuel use.

When used with an advanced fuel cycle, Generation IV reactors can produce up to a one hundred-fold improvement in uranium utilisation. Additionally, advanced fuel recycling options enable the reduction of the volume and radiotoxicity of the ultimate waste to be stored in deep geological repositories.

Generation IV reactors can be built with a range of sizes, including as SMRs. In fact, most of the near term commercial prospects for Generation IV reactors have the capacity range of SMRs (up to 300 MWe). Larger Generation IV reactors are also in operation or under construction in China, India and Russia. With several innovative concepts that have been under development for decades, commercial deployment is now expected as early as the early 2030s for the most mature Generation IV SMRs.

Thirteen countries and the European Union are advancing the development of Generation IV reactors through multilateral collaboration under the aegis of the Generation IV International Forum (GIF). GIF is a multinational co-operative endeavour organised to carry out the research and development needed to establish the feasibility and performance capabilities of the next generation nuclear systems. Six systems are under consideration: very high temperature reactors (VHTRs), molten salt reactors (MSRs), sodium-cooled fast reactors (SFRs), supercritical water-cooled reactors (SCWRs), gas-cooled fast reactors (GFRs) and lead-cooled fast reactors (LFRs).

Figure 12. **Generation IV systems**



Source: GIF (2021).

Nuclear hybrid energy systems including hydrogen

To understand the full potential of nuclear energy to contribute to global decarbonisation, it is helpful to take a system level view, to consider how nuclear energy can be integrated within broader energy systems, and how energy systems can be coupled with other industrial sectors to achieve maximum efficiencies and emissions reductions.

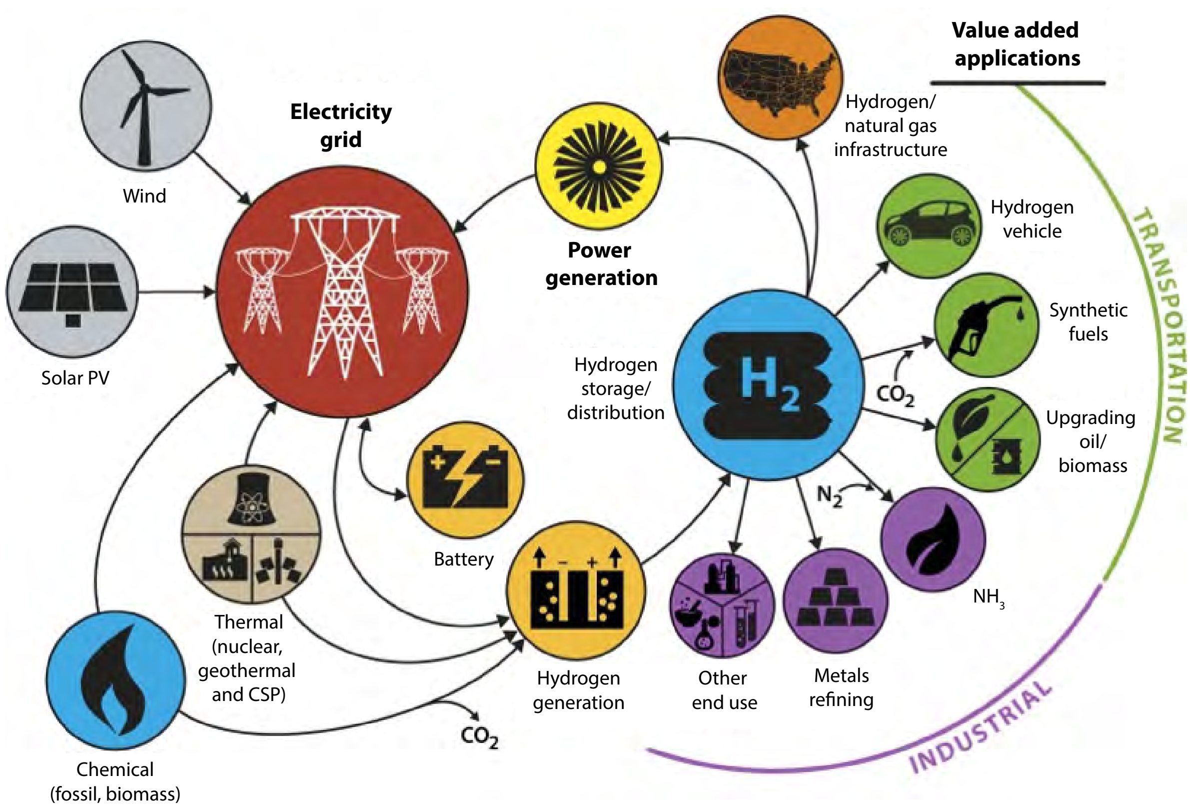
The term "hybrid energy systems" can be used to refer to several approaches:

- Scenarios where one energy source provides multiple useful outputs (such as combined heat and power);
- Scenarios where multiple energy sources are integrated to provide reliable power (such as variable renewables coupled with batteries and diesel backup to provide electricity to a remote micro-grid);
- Scenarios where multiple energy sources are integrated to provide multiple outputs (such as variable renewables and nuclear energy integrated to provide power to a grid and to produce hydrogen).

Hybrid energy systems are tightly coupled systems designed to maximise fuel utilisation and profitability across sectors as well as the overall system reliability (Arent et al., 2021). These types of systems are more complex, involving dynamic and multi-scale interactions. Nuclear hybrid energy systems are hybrid energy systems that include nuclear energy, for power or non-power applications.

Nuclear power could play a key role in hybrid energy systems as a source of both low-carbon heat and electricity. In hybrid systems, nuclear generators could shift from electricity to heat generation depending on price signals and other demand patterns and system constraints. The possibility to produce either electricity or heat for multiple applications can enhance flexible operations while maintaining high capacity factors. Such operational modes can therefore have a positive impact on the economics of nuclear power.

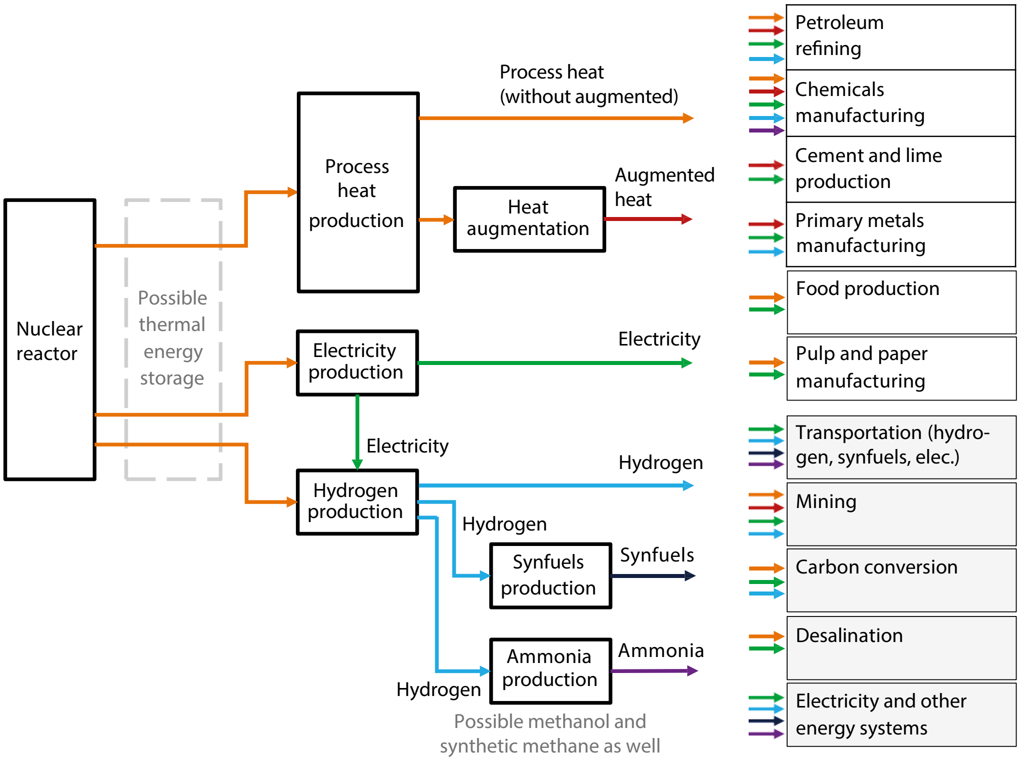
Figure 13. **Notional hybrid energy system**



Source: Bragg-Sitton and Boardman (2017). Graphic created by Dr Bryan Pivovar, NREL.

Nuclear reactors could serve a wide range of applications and demands: electricity for the grid, electricity for hydrogen production from electrolysis, heat to be stored in thermal storage facilities, and process heat for multiple industrial applications.

Figure 14. **Notional nuclear hybrid energy system**



Note: The "nuclear reactor" box represents, existing reactors, large Generation III new build, and SMRs, both light water reactors and advanced technologies

Source: Foss et al. (2021).

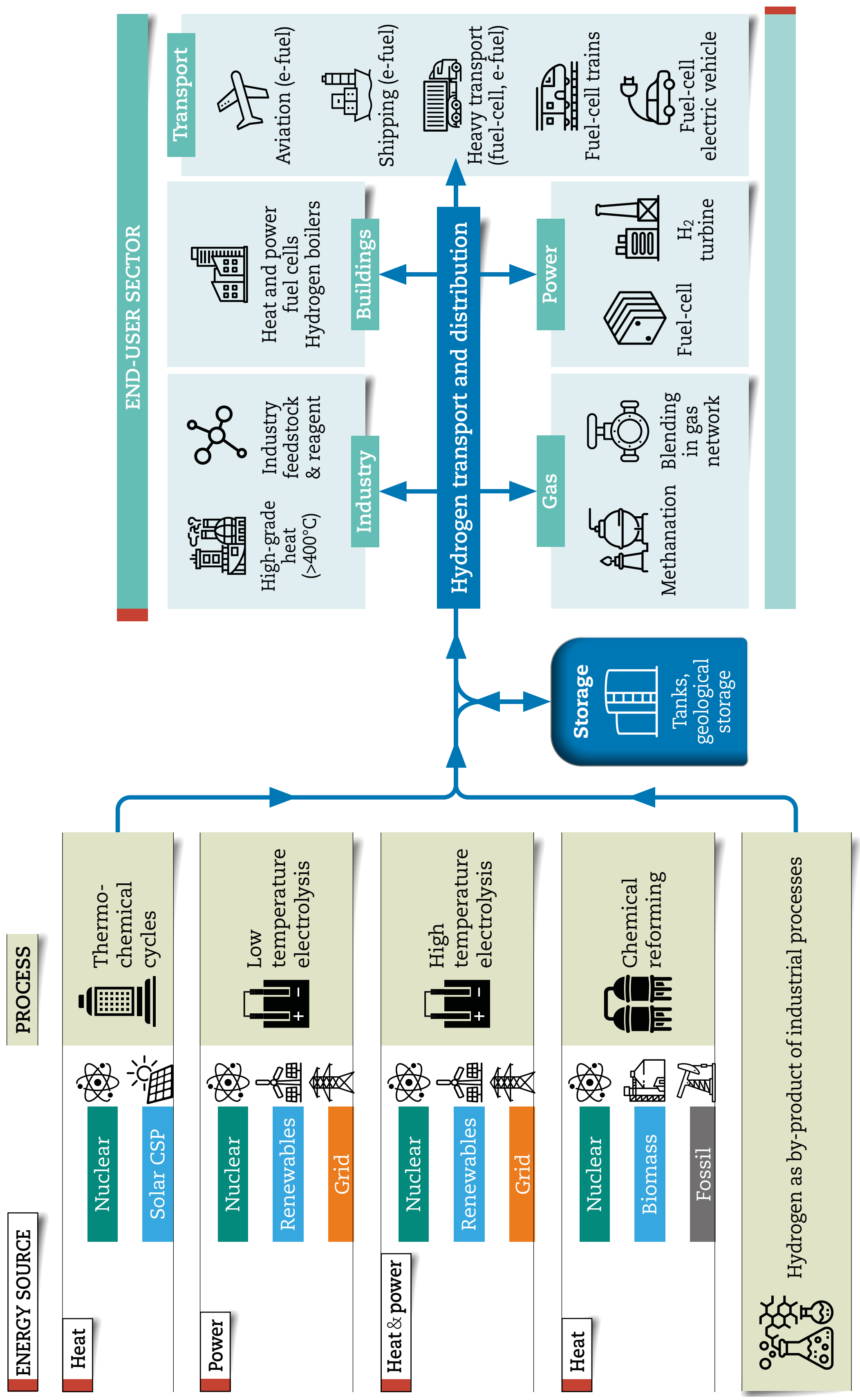
The extent of emissions reductions enabled by the integration – or hybridisation – of energy systems depends on the magnitude of non-emitting energy sources deployed in the system, but it is the systems level integration that enables more extensive, more rapid, and more cost-effective deployment of various non-emitting technologies by coupling them with other enabling non-emitting technologies. Notably, integration of nuclear with variable renewables provides much needed grid flexibility and enables deeper penetration of variable renewables on the grid. Nuclear energy also provides cost-effective and large-scale options for low-carbon hydrogen production from existing and available nuclear technologies. Future nuclear innovation may offer increased efficiencies, but existing nuclear technologies are already available at the scale required to enable variable renewables and low-carbon hydrogen production to meet near-term growing demand and aggressive emissions reductions targets.

There is momentous interest around the world in hydrogen as a potential part of the solutions to climate change. Hydrogen has the potential to contribute to decarbonisation strategies if it is produced with low-carbon sources and its production does not crowd out decarbonisation of other parts of the energy system, for example, by competing for low-carbon electricity where supply is limited.

The hydrogen economy, along with hybrid energy systems more broadly, is a complex concept characterised by complex and dynamic interactions across energy sub-systems. Hydrogen cannot be modelled as simply another source of demand for the electricity system. Since hydrogen can also be a tool for long-term storage and a vector for sector coupling, it can be both a source of supply as well as demand, changing the energy system dynamics.

It is useful to think of the hydrogen economy in terms of hydrogen production process, hydrogen transportation, distribution and storage, and hydrogen applications or end-uses (Figure 15).

Figure 15. **The hydrogen economy – energy sources, production processes and end-uses**



Since hydrogen occurs naturally only in compound forms with other elements – for example as water (H_20) or as hydrocarbons (containing both hydrogen and carbon) such as natural gas, coal, and petroleum – hydrogen for the energy transition (H_2) must be produced. It can be produced from a variety of technologies and feedstocks (i.e. material inputs), each with different carbon intensities.

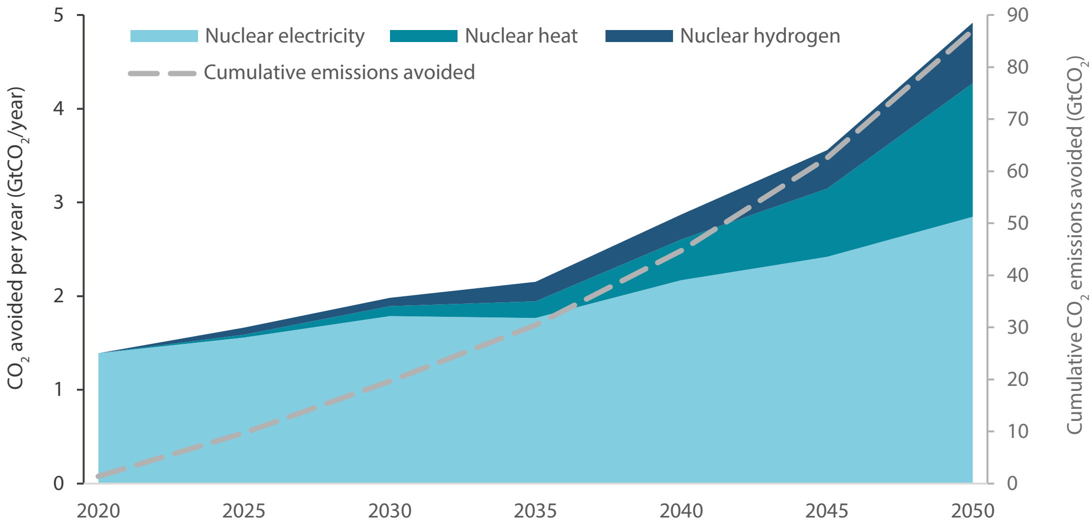
Some of the most promising near-term large-scale hydrogen flows start with electrolysis, to produce hydrogen for industry (e.g. refining, ammonia) and transport. Demand for electricity to produce hydrogen from electrolysis expected to reach as much as 15 000 terrawatt-hours by 2050, with significant emissions implications depending on whether the electricity is non-emitting of fossil generated.

Irrespective of the carbon intensities of hydrogen production methods, once it has been produced, hydrogen can be stored and transported for a range of end-uses including fuel cells for transport or buildings, as well as a range of additional industry applications (e.g. iron and steel making). Hydrogen can also be used to produce synthetic fuels (e-fuels) that can be used in particular for transport (e.g. haulage, shipping, aviation). Hydrogen research and development is active in every area of the hydrogen economy, across production methods, storage and transportation methods, and end-uses.

More than 50% of hydrogen demand by 2030 is projected to be driven by new applications, for example hydrogen blended into gas networks and hydrogen for power generation. Beyond 2030, growth in hydrogen demand is expected to be driven primarily by the transport sector, roughly half from road and half from aviation and shipping (IEA, 2021).

Taken together, nuclear hybrid systems with non-electric applications including hydrogen can contribute to avoiding nearly 23 gigatonnes of cumulative emissions between 2020-50 (with respectively 15 gigatonnes of emissions for nuclear heat and 8 gigatonnes of emissions for nuclear hydrogen). This represents more than one third of the overall contribution of nuclear energy to climate change mitigation, with the other two thirds being delivered by nuclear power. In addition, the full role of nuclear will not be limited to these directly emissions avoided. Through nuclear hybrid systems, nuclear energy will be a source of flexibility to support variable renewables integration, enabling them to contribute to emissions reductions.

Figure 16. **Carbon emissions avoided by nuclear power and non-power applications (2020-2050)**

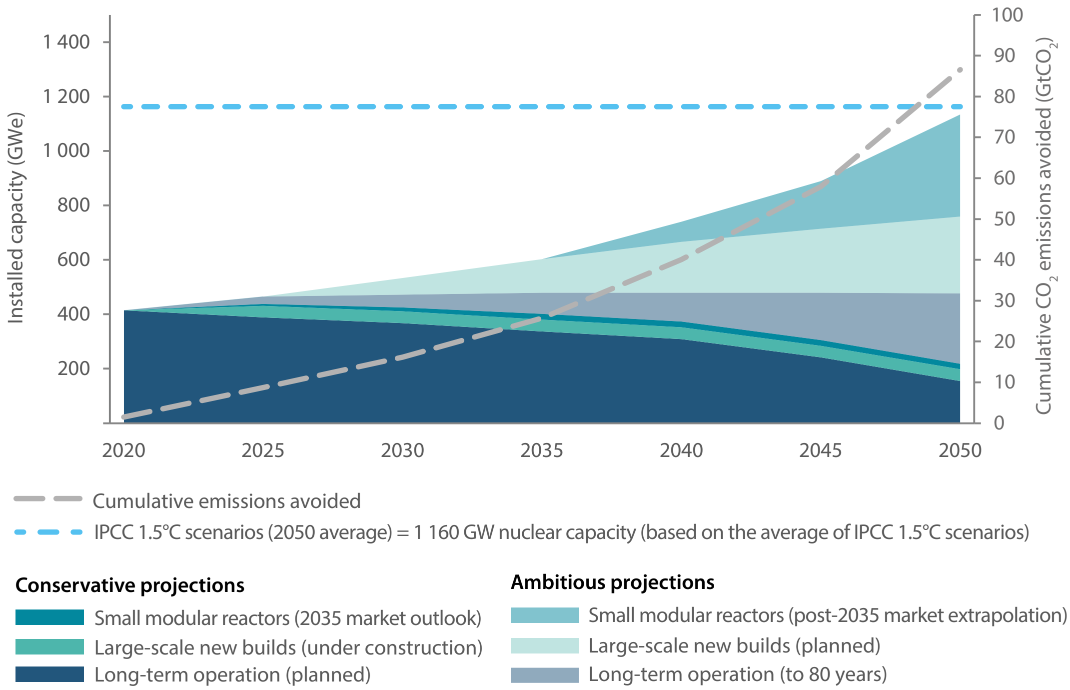


Full potential of nuclear contributions to net zero

Taken together, the contributions of long-term operation, new builds of large-scale Generation III nuclear technologies, small modular reactors, nuclear hybrid energy and hydrogen systems begins to reveal the full extent of the potential for nuclear energy and nuclear innovations to play a significant and growing role in pathways to net zero by 2050.

The average IPCC 1.5°C scenario requires nuclear energy to reach 1 160 gigwatts of electricity by 2050. This is an aspirational target but it is not beyond reach. It can be achieved through a combination of long-term operation, large-scale Generation-III new builds and small modular reactors, as illustrated in Figure 17. Reaching this target would avoid 87 gigatonnes of cumulative emissions between 2020 and 2050, positioning nuclear energy's contribution to preserve 20% of the world's carbon budget consistent with a 1.5°C scenario. This would be equivalent to avoiding nearly three years of global carbon emissions at 2020 levels.

Figure 17. **Full potential of nuclear contributions to net zero**



These estimates are not forecasts but represent what could be achieved with timely enabling policy decisions.

Box 4: **The availability of uranium to support nuclear contributions to net zero**

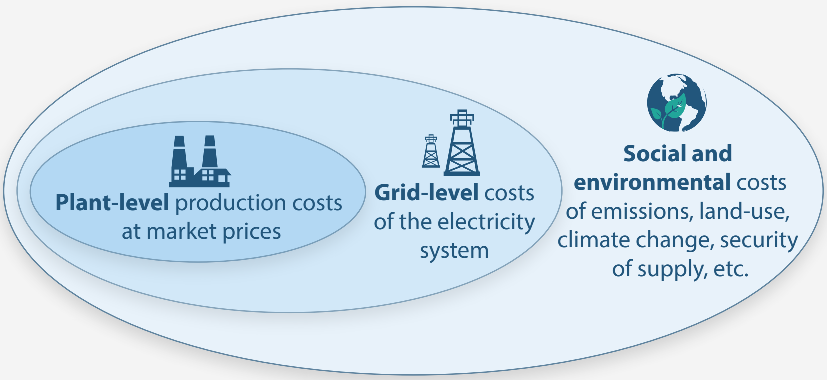
Excerpt from *NEA/IAEA Uranium 2020: Resources, Production and Demand* (Red Book):

> "Sufficient uranium resources exist to support continued use of nuclear power and significant growth in nuclear capacity for low-carbon electricity generation and other uses (e.g. heat, hydrogen production) in the long term. Identified recoverable resources, including reasonably assured resources and inferred resources (at a cost <USD 260/kgU, equivalent to USD 100/lb U_3O_8) are sufficient for over 135 years, considering uranium requirements as of 1 January 2019. However, considerable exploration, innovative techniques and timely investment will be required to turn these resources into refined uranium ready for nuclear fuel production and to facilitate the deployment of promising nuclear technologies.
>
> In the wake of recent significant reductions in uranium production and the effects of COVID-19 pandemic, the coming challenges are likely to be those associated with constrained investment capabilities, as a result of depressed market conditions that will push the industry to optimise its activities still further."

Box 5: The System Costs of Electricity

To understand the costs of electricity provision requires systems level thinking.

Figure 18. **Understanding system costs of electricity**



Source: Adapted from NEA (2012).

The first level of analysis is **plant-level costs** of generation, which include, amongst other costs, the costs of actual concrete and steel used to build the plant, as well as fuel and human resources to operate the plant. These plant-level costs are typically referred to as the levelised cost of electricity (LCOE), and they may include some costs that were previously considered as externalities, for example if there is a price on carbon or a legislated requirement to internalise the end of life cycle costs into plant-level costs.

The next level of analysis takes into account **grid-level system costs**. These are the costs that generating units impose on the broader electricity system – including the costs of maintaining a high level of security of supply at all times as well as delivering electricity from generating plants to customers – in other words in addition to production, they include connection, distribution, and transmission costs. Most importantly, grid-level costs include the costs associated with compensating for the variability and uncertainty in the supply from generating plants. This includes the costs of additional dispatchable capacity to account for the variability of certain renewables such as wind and solar PV and for maintaining spinning reserves that can be ramped up when the production of variable sources falls short of forecasts.

The final level of analysis addresses the full costs, including the **social and environmental costs** that different technologies impose on the well-being of people and communities, including negative externalities like atmospheric pollution, impacts on land-use and biodiversity, as well as, in certain cases, positive externalities such as impacts on employment and economic development, or spin-off benefits from technology innovation. These are the externalities that are not accounted for in plant-level costs or grid-level system costs.

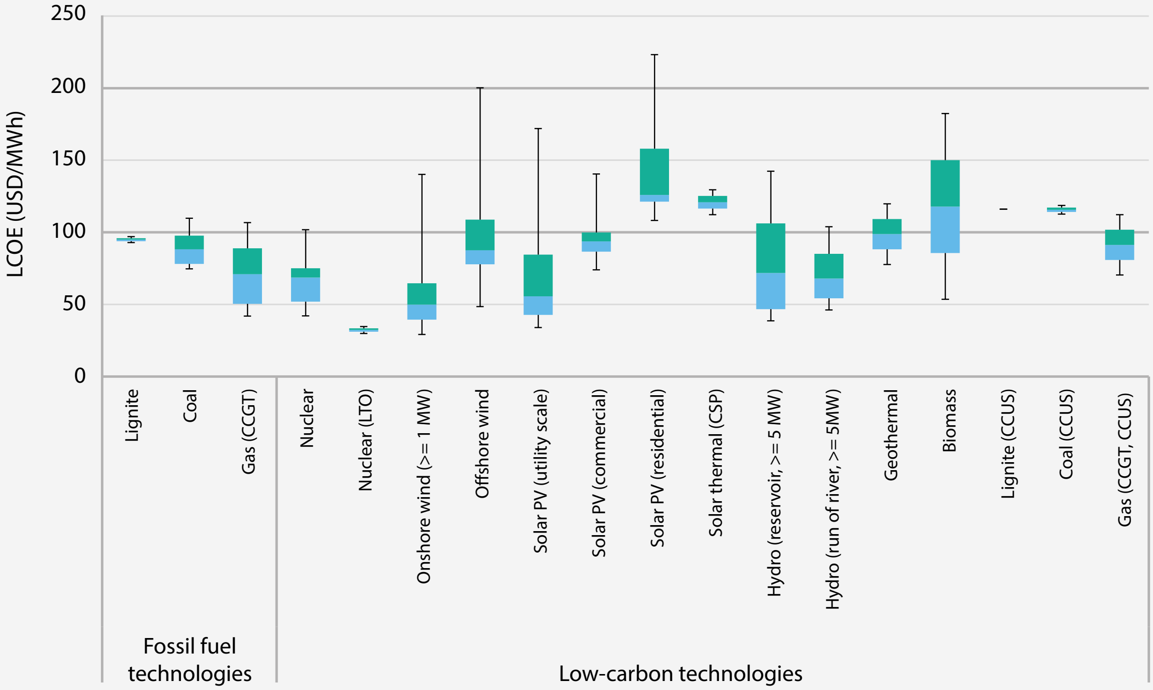
The combination of plant-level costs, grid-level systems costs, and full social and environmental costs creates a framework that allows policymakers to compare the costs of different generating options – comparing apples to apples, not apples to oranges. To do so requires a systems level perspective.

Total economic system costs, then, are defined as **plant-level generating costs** plus **grid-level system costs**. Taking this systems level perspective includes:

- **Profile costs** – the grid-level costs imposed by variability or intermittency.
- **Balancing costs** – the grid-level costs imposed by uncertainty in generation.
- **Connection, distribution, and transmission costs** – the costs of delivering electricity from distributed power generation to customers.

To be clear: while all technologies impose some system costs, variable, intermittent, and uncertain sources of power generation impose far greater grid-level system costs, which is why it is so important to take a systems level perspective when comparing costs of variable renewables with nuclear, baseload hydro, and fossil generation.

Figure 19. **Levelised cost of electricity (LCOE) for different sources of electricity**



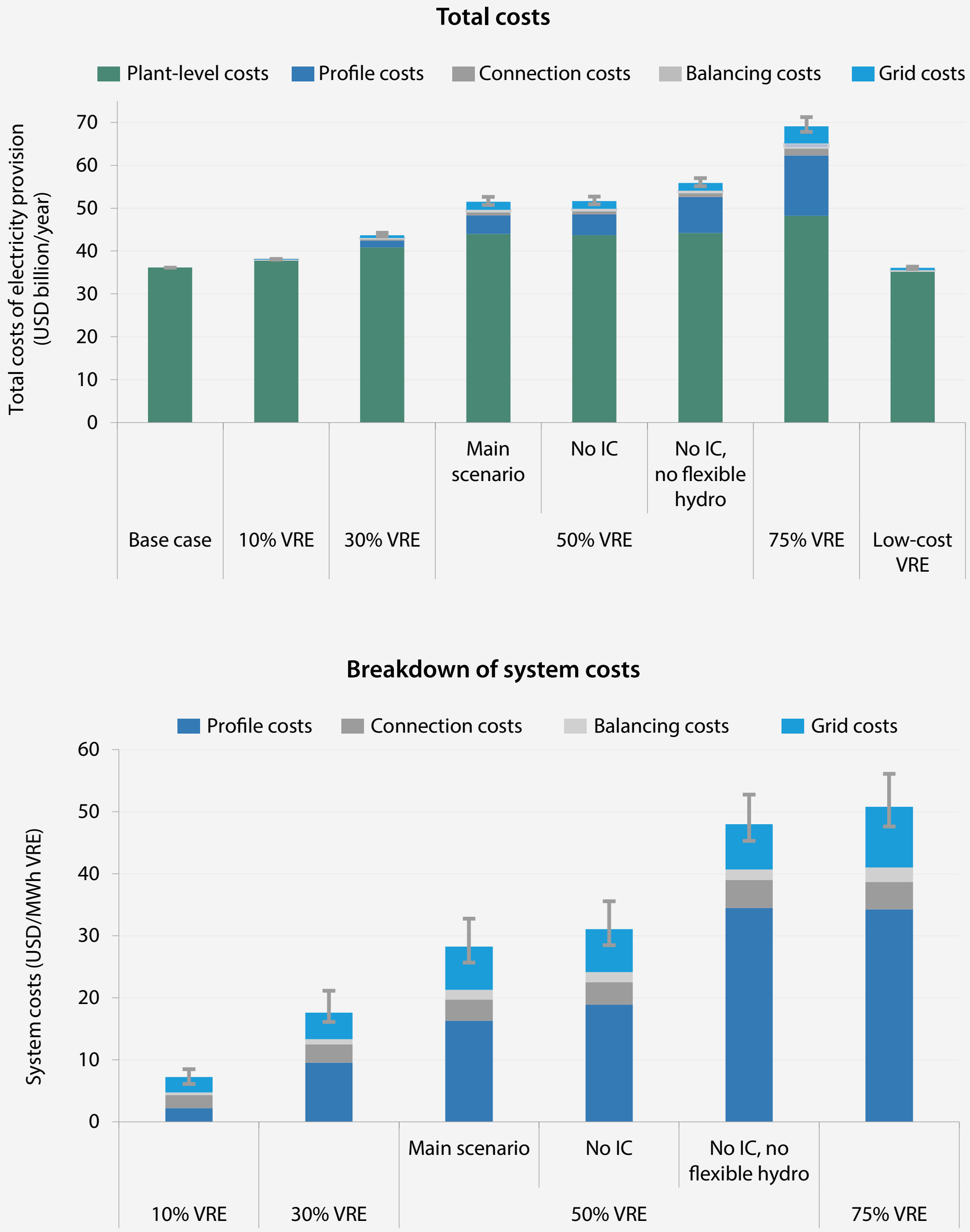
Source: IEA/NEA (2020).

The first step for cost comparisons remains LCOE analysis. Presented in Figure 19, an analysis of system costs from more than 20 IEA and NEA member countries concluded that the lowest cost option for generating electricity is long-term operation of nuclear power plants (IEA/NEA, 2020). Equally notable was the finding about the range of costs for solar and wind generation, which depend heavily on regional endowments and conditions. These results can be reproduced, and tested with different input parameters, with the IEA-NEA online LCOE calculator at: www.oecd-nea.org/lcoe.

LCOE analysis, considering technologies one by one, only tells part of the story though. It is crucial also to assess the interaction of different technologies in a mix of generating sources with different shares in the electricity supply. In order to analyse this, a recent NEA study compared a range of scenarios, starting with a base case with 0% variable renewables, then considering mixes with increasing shares of variable renewables, up to 75% variable renewables in the mix.

As shown in Figure 20, total costs rise as the share of variable renewables increases. This is due, in part to the rise in average plant-level costs, which in reality depends on the regional endowments and meteorological conditions in different countries. Under all circumstance, however, the system costs will rise as the growing share of variable renewables imposes greater costs on the grid for stability and flexibility.

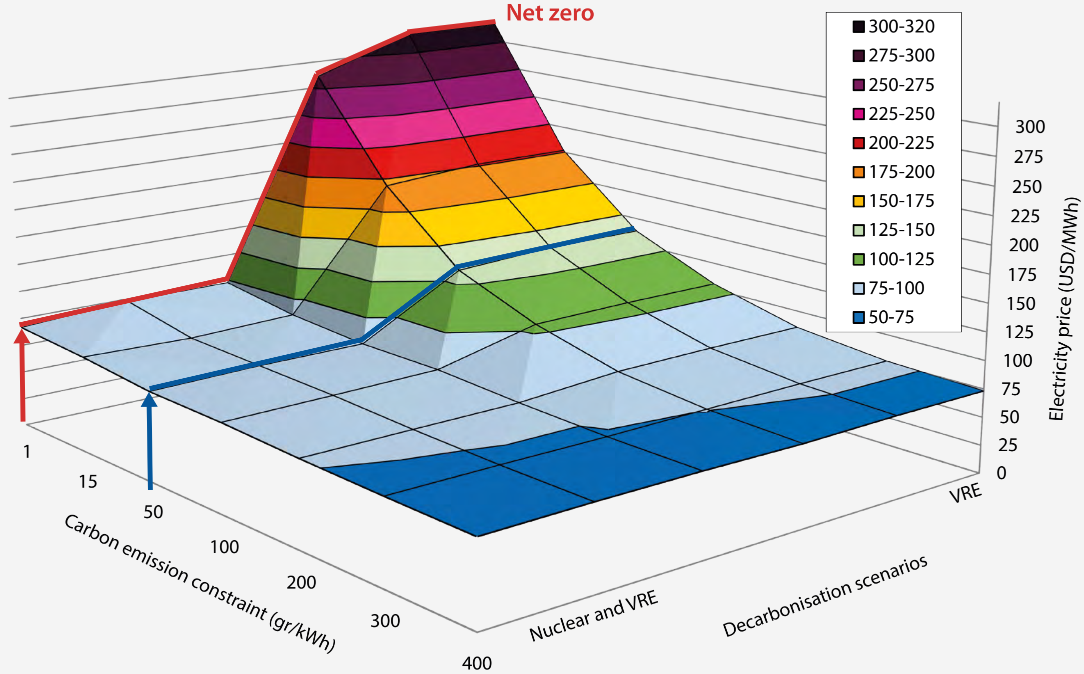
Figure 20. **Total costs for different mixes of electricity (with a carbon constraint of 50 grams per kWh)**



Source: NEA (2019).

Figure 20 shows the break-down of system costs as the share of variable renewables grows from 10% to 75% of the mix, including profile costs (to compensate for variability and intermittency), connection, distribution, and transmission costs, and balancing costs (to compensate for uncertainty). A key finding is that profile costs (to compensate for variability and intermittency) are the dominant driver of increasing total costs as the share of variable renewables grows.

Figure 21. **Total costs for different mixes of electricity (driving to net-zero emissions)**



Source: Based on Sepulveda (2016).

System costs are also a function of overall carbon constraints. Figure 21 shows the total costs (the sum of plant-level and grid-level system costs) as a function of carbon constraints (on the horizontal axis pointing left) and share of variable renewables (on the horizontal axis pointing right). The previous 2-dimensional graph (shown in Figure 20 above) illustrated how total costs increased significantly in scenarios with high shares of variable renewables. On the three-dimensional graph (shown in Figure 21), this is represented by the blue line, which cuts the three-dimensional image at a carbon constraint of 50 grams per kilowatt hour.

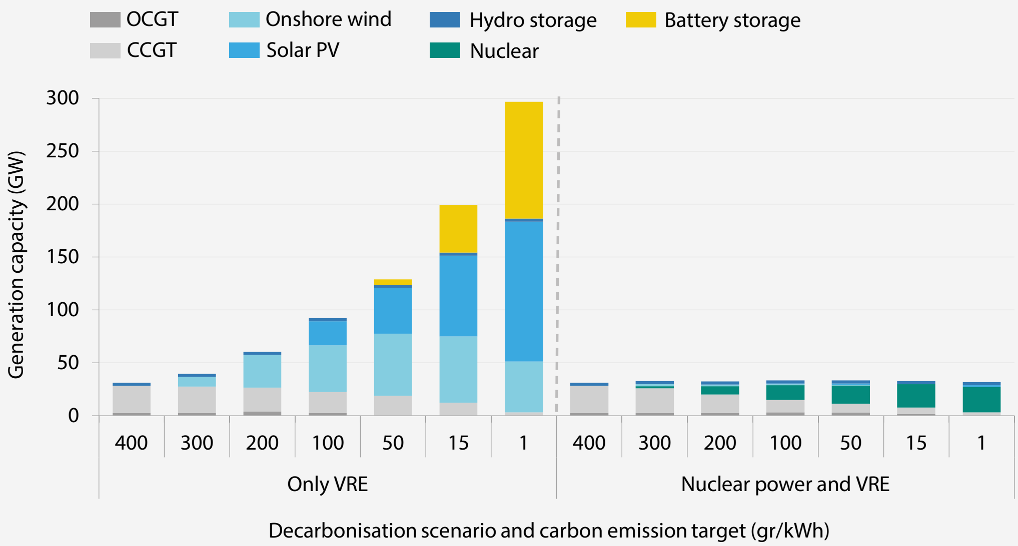
The 3-dimensional graph shows the effects on total costs as carbon emissions are increasingly constrained. The red line shows what happens to total costs when carbon constraints reach net-zero emissions. The relationship between the share of variable renewables and systems costs, driven by profile costs to compensate for variability, is even more pronounced when carbon constraints become more stringent.

The policy implications of these systems costs findings are significant. It may be possible to reduce emissions to meet 2030 targets by growing the share of variable renewables in the mix. However, the costs of reaching net zero with high shares of variable renewables are likely prohibitive. *Why?* In part, because initially, as variable renewables are introduced, they can be backed up with a low cost option, which in the absence of a serious carbon constraint is likely to be natural gas. But eventually, in a carbon constrained world, the options for backing up variable renewables become increasingly expensive. Dispatchable hydro power and nuclear energy are the only economic options while batteries remain prohibitively expensive for anything other than very short-term storage.

Put another way, policies to achieve 2030 targets may first appear like progress towards 2050 net zero targets, but they may be deceiving. Taking coal offline and replacing it with a mix of variable renewables and natural gas may enable countries to reach 2030 emissions reduction targets. However, to get to net zero, countries will likely also need to take natural gas offline. If there has already been a significant build-out of variable renewables to reach 2030 targets, replacing natural gas becomes increasingly difficult and costly.

This is illustrated in Figure 22 (left side). To reach net-zero with high shares of variable renewables, natural gas is replaced with a mix of battery storage and hydro storage. Owing to the variability of solar and wind power, greater and greater generating capacity (in the form of variable renewables plus batteries and storage) is required, which also contributes to growing total costs. Meeting demand with a mix of variable renewables plus batteries and storage requires much more built capacity than a grid based on baseload and dispatchable sources of power, like nuclear energy.

Figure 22. **Driving to net zero with different mixes of generation capacity**



Source: Based on Sepulveda (2016).

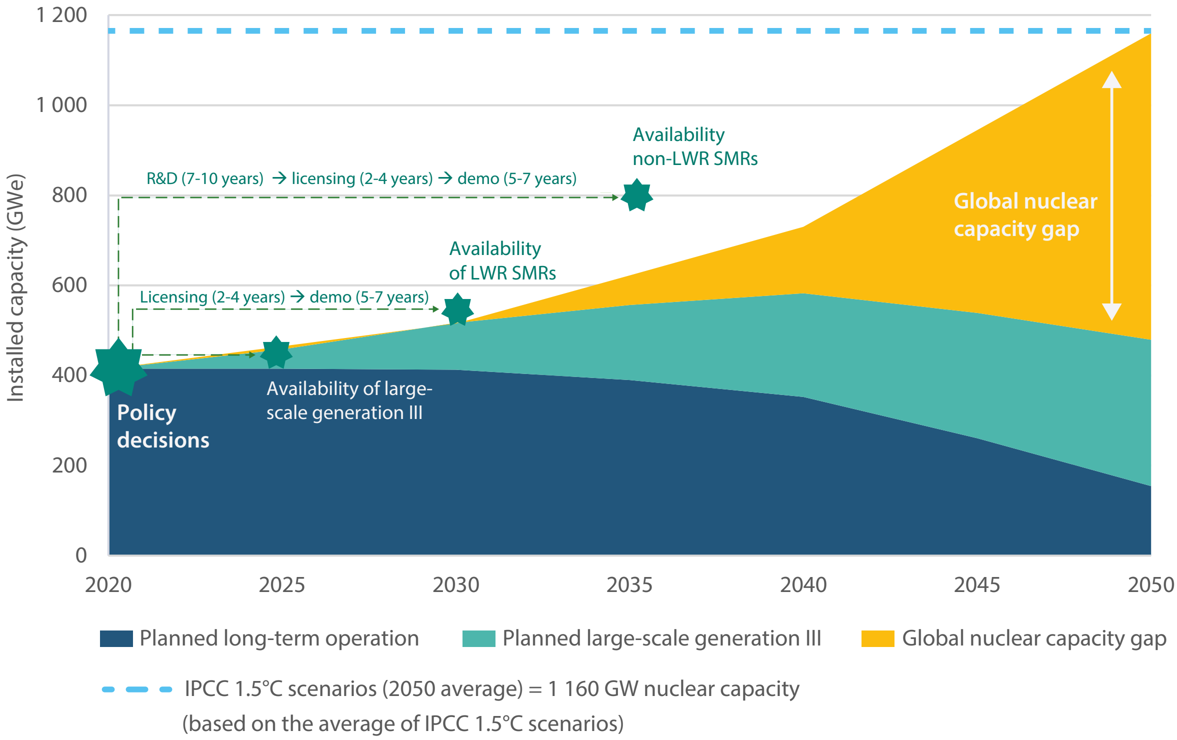
Figure 22 (right side) also sets out the results of an optimisation model, which concludes that the most cost effective replacement for natural gas as countries drive to a net-zero future is nuclear energy (in orange). The more stringent the carbon constraint, the more indispensable becomes nuclear energy.

Challenges and opportunities

While the potential exists for nuclear energy to play a much larger role in global climate change mitigation efforts, various enabling conditions must be met for this technology to fulfil its potential.

Every year, the IEA *Tracking Clean Energy Progress* reports stress that efforts to grow and decarbonise the power sector broadly, including growing the nuclear power, are not on track to meet climate targets. According to current policy trends, nuclear capacity in 2050 will amount to 479 gigawatts – well below the target of 1 160 gigawatts of electricity set out above. As Figure 23 below shows, addressing this policy gap with nuclear new builds – whether large Generation III, Generation IV, or small modular reactors – will require near-term policy decisions to enable their deployment over the next three decades.

Figure 23. **Global installed nuclear capacity gap (2020-2050)**



Source: IEA (forthcoming).

The existing nuclear fleet, with long-term operation, will continue to make an important contribution past 2050 (shown in yellow in Figure 23). Planned nuclear new builds of Generation III reactors will also play a role (shown in green in Figure 22). Even with these important contributions, there is a projected gap between the *minimum required global installed nuclear capacity* and *planned global nuclear capacity*. This global nuclear capacity gap is shown in red on Figure 22, and reaches nearly 300 gigawatts by 2050.

Even though the global nuclear capacity gap does not become apparent until 2030-2050, there is an urgency to action. Owing to the timelines for nuclear projects, decisions must be taken years in advance to ensure adequate global installed nuclear capacity for the net zero scenario. Targeted policies, sustained investment and international co-operation are needed to reduce project costs, improve deployment timelines, build public confidence, and address financial barriers.

Recommendation 1: Acting now

Governments and *industry* should work together on an urgent basis to demonstrate and commercially deploy nuclear energy innovations before the window of opportunity closes to meet the 1.5°C target.

Reducing project costs

Nuclear projects are capital intensive, with the cost of capital often representing up to 75% of production costs. The nuclear sector also has a negative reputation among financiers and policy makers for project delays and cost overruns. Nuclear energy projects face challenges competing with fossil energy in the absence of a price on carbon, as well as challenges competing with wind and solar power in markets that fail to value dispatchability.

While NEA analyses have demonstrated that nuclear energy is highly competitive with other low-carbon technologies when costs are considered at the level of electricity systems, potential customers of nuclear designs have concerns about project costs. At the plant level, while long-term operation remains one of the lowest cost options for low-carbon electricity in OECD countries, nuclear new builds are often considered as a high cost option, in large part due to a legacy of cost overruns over the last decade. The ability of the nuclear sector to demonstrate that it can meet its cost reduction objectives – be it for large Generation III, Generation IV, or small modular reactors – will play in key role in addressing the perception of nuclear construction risks.

Structural market reforms are needed to address the impacts of greater integration of variable renewables and their associated system costs. More generally, decarbonising the electricity sector in a cost-effective manner while maintaining high levels of electricity security requires policy makers to recognise and equitably allocate system costs to the responsible technologies (NEA, 2019). Fostering competitive short-term markets and ensuring adequate capacity and flexibility, as well as transmission and distribution infrastructures, are key policy measures to support the internalisation of system costs by market participants.

Last but not least, new business models will also be required to support the emergence of integrated energy systems where nuclear would play on different energy markets, potentially providing both low-carbon electricity and heat to a range of different customers.

Recommendation 2: Understanding and reducing costs

The *nuclear sector* should implement recommendations from the NEA (2020) study *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders* to ensure that the sector meets cost objectives.

Governments should take a systems level perspective when developing electricity policies to ensure that markets value desired outcomes, such as low carbon baseload, dispatchability, and reliability.

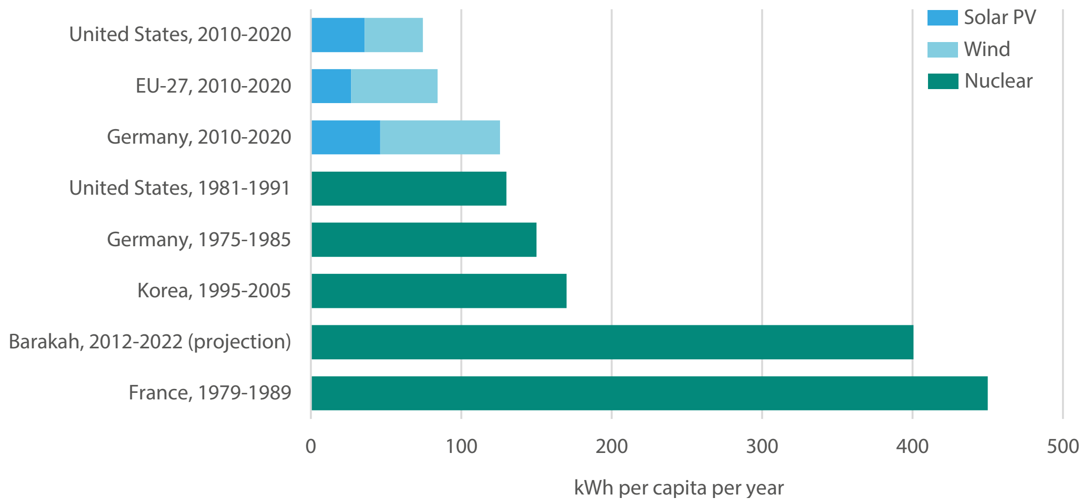
Improving deployment timelines

Over the last decade, delays with nuclear new build projects have brought into question the relevance of nuclear power to provide a timely contribution towards decarbonisation efforts. Compared to variable renewables whose construction can take 1 or 2 years, nuclear power plants construction takes several more years and can easily expend beyond a decade once planning and licensing processes are taken into account.

Conversely, historical and recent experience show that under the right policy frameworks and a robust programmatic approach, nuclear power can be a low-carbon technology with rapid delivery times and with the highest rate of annual increase of electricity generation per capita. This was the case historically for countries such as France and jurisdictions such as Ontario in Canada that have both decarbonised their electricity mix in less than two decades with nuclear energy and hydropower.

Today, the Barakah project in the United Arab Emirates (UAE) demonstrates that such rate of deployment can also be achieved with large Generation III nuclear reactors. In China and Korea, countries in more advanced stages of nuclear construction learning, construction lead-time are around in average of 5-6 years, or even lower.

Figure 24. **Average annual increase of low-carbon electricity per capita during decade of peak scale-up**



Harmonising codes and standards and regulatory approaches can also be a key enabler for the deployment of nuclear power, in particular for new technologies such as SMRs. However, the advances introduced by innovative nuclear technologies and reactor designs such as SMRs and advanced reactors may deviate from current licensing regimes and practices. The limited regulatory experience with novel designs poses a significant challenge in demonstrating and approving their safety case.

SMRs and advanced reactors could be viewed as an opportunity for the early development of international collaborative approaches for the harmonisation of licensing frameworks and codes and standards (NEA, 2021a). These topics have already been extensively discussed for large reactors and the experience gained could be applied to these innovative reactors. For instance, at the level of industrial codes and standards harmonisation, the WNA CORDEL working group has made progress inspired by the example of the aircraft industry. More generally, these issues are currently discussed by the NEA and the IAEA. Further, the Multinational Design Evaluation Programme (MDEP) administered by the NEA encourages multinational convergence of codes, standards and safety goals.

Recommendation 3: Addressing timelines

Governments and industry should learn from successful examples of rapid deployment of nuclear to decarbonise electricity grids, such as France and Ontario (Canada) in the 1980s and the UAE in 2010-present. These examples chart a path for rapid decarbonisation of electricity grids that are still heavily reliant on coal and fossil energy.

Regulators should collaborate to harmonise licensing approaches to enable efficient fleet deployment of nuclear innovations across international boundaries.

Building public confidence

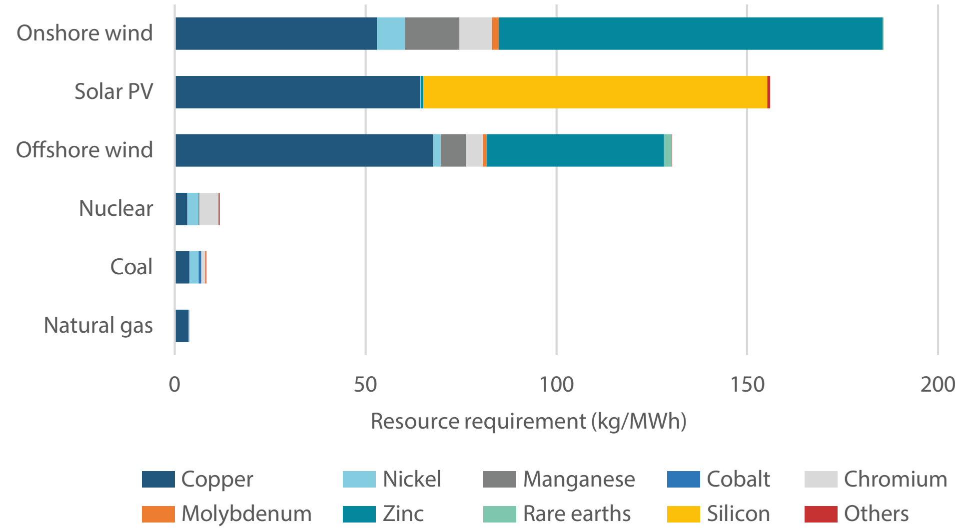
Public confidence in nuclear energy is mixed and varies greatly by region and demographic. Commonly cited concerns include questions about long-term waste management, safety and security. Building and maintaining public confidence is essential for all nuclear projects, from mining to research and development, operations, and waste management.

Building trust is central to building public confidence, and requires sustained investments in open and transparent engagement as well as science communication. A common mistake, however, is to assume that public confidence is primarily a communications issue, when in actuality, public confidence is much more complex, touching on issues of trust, values, culture, and benefits sharing, among others.

Public opinion research, although not uniform, suggests that in some areas proximity and familiarity with nuclear power operations tend to be correlated with openness to nuclear energy (Wang and Kim, 2018). In addition, concern about climate change also tends to be associated with greater openness to nuclear energy (Anderson and Coletto, 2019, Bisconti, 2021).

While energy technological choices are increasingly driven by climate change considerations, other environmental factors are also expected to play a growing role, either as limiting factors for the development of some technologies, or because of heightened emphasis on impacts for biodiversity and other sustainable development goals. These considerations include in particular factors such as land footprint and critical minerals requirements. The significant increase in critical mineral requirements in low-carbon scenarios means that the energy sector is emerging as a major source of demand in critical mineral markets (IEA, 2021d). As shown in Figure 25 and Figure 26 below, nuclear power is the low-carbon source of electricity that scores best for both requirements in terms of critical minerals[1] and land footprint. Shining a light on these comparisons could have important effects on public confidence in nuclear energy projects.

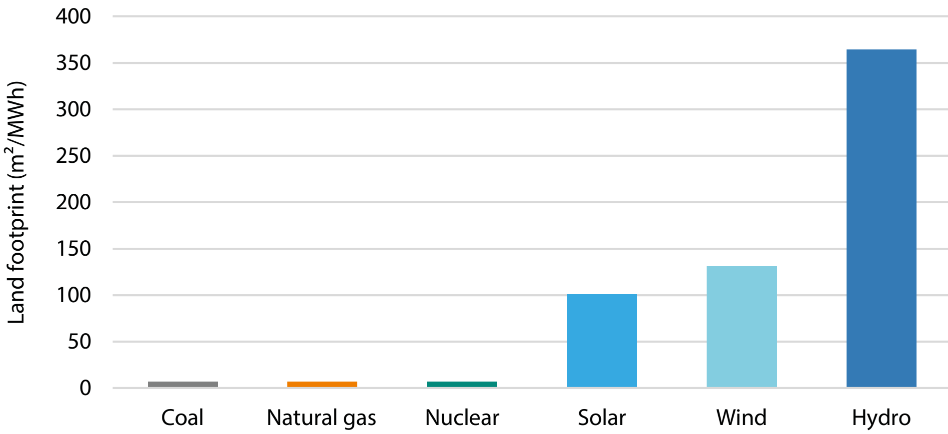
Figure 25. **Critical minerals for different sources of electricity**



Source: Analysis based on IEA (2021) data.

1. Uranium is not within the scope of the IEA analysis that focuses on mineral requirements for production of equipment, and not for operations. Uranium long-term supply-demand adequacy is assessed periodically in the NEA/IAEA "Red Book" (NEA/IAEA, 2021).

Figure 26. **Land footprint for different sources of electricity**



Source: Analysis based on Strata (2017).

Recommendation 4: Building public confidence

Governments and industry should engage the citizenry to build trust and public confidence, ensuring that public dialogues about energy options are evidence-based. This involves addressing misinformation and ensuring that a realistic conversation about the pros and cons of various options is facilitated.

Addressing financial barriers

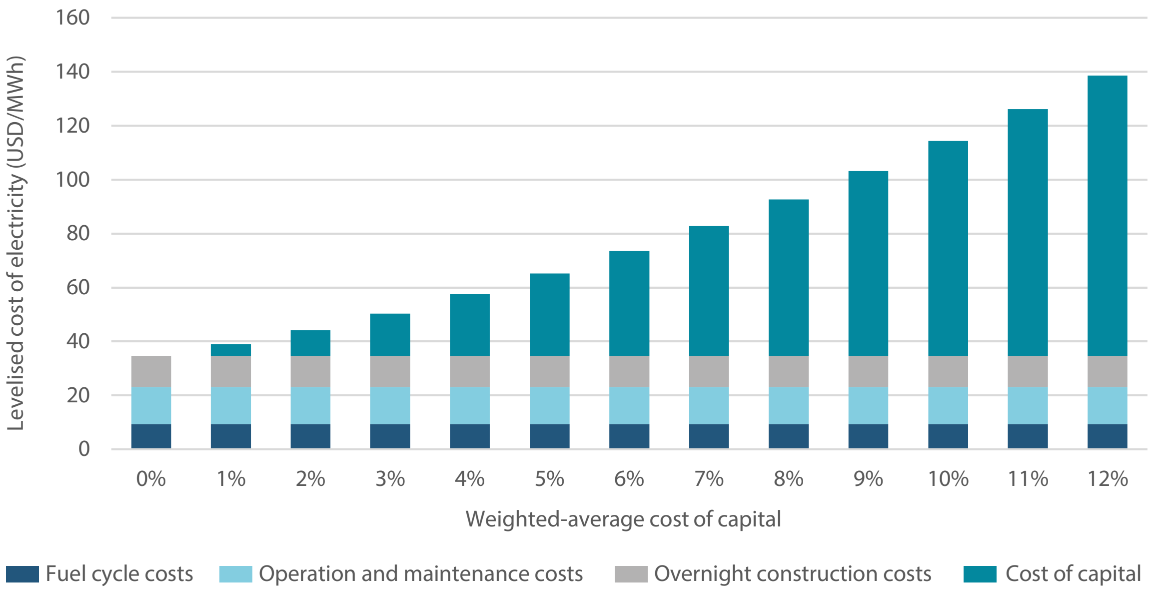
The cost of capital is one of the main drivers of the levelised cost of nuclear power. As shown in Figure 20, an increase from 6 to 9% on the nominal weighted average cost of capital (WACC) effects an increase of approximately 50% of the levelised cost[2].

All capital-intensive infrastructure projects – including but not limited to nuclear energy projects – depend to some extent on direct or indirect support and risk-sharing from governments and international financial institutions. This can include direct funding, but also enabling policy frameworks that allow an efficient allocation of risks and for nuclear energy projects to compete on their merits on equal footing with other non-emitting energy projects.

The right policy frameworks can help to address construction and market risks. Depending on national context and project characteristics, several financing models can be considered for nuclear new build projects with governments actively helping to mitigate risks and supporting financing. Governments are uniquely positioned to play this role, leveraging historically low interest rates and relatively abundant private capital in OECD countries, to lower the cost of capital for capital intensive nuclear energy projects.

2. With the assumption of an overnight cost of USD 4 500/KWe and a lead-time of 7 years.

Figure 27. **Levelised cost of nuclear power for a range of weighted-average costs of capital**



Source: NEA (2020).

Governments should also consider taking a direct equity stake in new nuclear construction projects, as the public sector has the lowest cost of capital in most OECD countries. Doing so could enable governments to be more proactively involved in project governance, including in activating its social benefits.

Multilateral development banks and international financial institutions also have role to play, in addition to national governments. Energy innovation, development and deployment policies should be technology-neutral and structured to incentivise desired outcomes, such as emissions reductions and security of energy supply. This includes taxonomies, as well as criteria for access to climate finance, development finance, and Environmental Social and Governance (ESG) finance. Labels and categorisation matter, as they are expected to influence and direct the flow of financing for years to come. Metrics should be applied consistently with similar levels of scrutiny across technology options, to allow technologies to compete on equal footing. In this way, efficiency is best achieved with technology-neutral policies and criteria.

Recommendation 5: Financing and investing

Governments should support a technology neutral approach that includes nuclear energy in taxonomies, climate finance, development finance, and ESG finance.

Governments should make investments in nuclear energy, including:

i. Investments to keep the cost of capital low;
ii. Investments focused on accelerating commercialisation of nuclear innovation (focused on pre-commercial technology readiness levels 3-7);
iii. Investments in nuclear regulators to ensure their readiness to regulate innovation; and
iv. Equity investments as well as other forms of investment in near-term nuclear new build projects.

Box 6: UN Climate Change Conference 2021 (COP 26)

COP 26 will take place in Glasgow between 31 October and 14 November 2021. This will be the first COP to take place after the Paris Agreement takes effect and the first opportunity for countries to review commitments and strengthen climate ambitions.

The UK Presidency has selected five key themes to structure the 2021 climate negotiations. Nuclear energy can support priorities across all five themes.

I. **Clean energy**: Accelerating the global transition to clean energy
   - **The role of nuclear energy**: As the largest source of low-carbon electricity in OECD countries and the second largest source of low-carbon electricity around the world after hydropower, nuclear energy is a key pillar in reaching net zero by 2050. All credible climate scenarios show a growing role for nuclear to meet the objectives of the Paris Agreement.

II. **Clean transport**: Driving the global transition to zero emission transport
   - **The role of nuclear energy**: Nuclear has a role to play as part of the clean electrification strategies that will underlie electric vehicles and electric transport, and as a means to produce low-carbon hydrogen and other synthetic fuels and ammonia.

III. **Nature-based solutions**: Actions that protect, manage and restore ecosystems to address societal challenges (e.g. climate change) while enhancing human wellbeing.
   - **The role of nuclear energy**: Among low-carbon sources of electricity, nuclear has one of the smallest environmental footprints, in particular with respect to critical minerals intensity and land use, and consequentially impacts on biodiversity.

IV. **Adaptation and resilience**: Improving the ability of natural and human systems to respond to climate change impacts before or after they have occurred (adaptation), or improving their inherent ability to absorb and withstand after an adverse event (resilience).
   - **The role of nuclear energy**: Adaptation will require reliable electricity grids. Nuclear power is a reliable, dispatchable, and resilient source of clean energy, owing to a combination safety culture, operational flexibility and continuous learning.

V. **Climate finance**: Investment in all of the above, as well as disinvestment from high-carbon industries.
   - **The role of nuclear energ**y: For all the reasons set out in this report, nuclear energy should be front and centre in discussions about taxonomies, climate finance, development finance, and Environmental Social and Governance (or ESG) finance. But there is work to do on this front. Decisions taken by governments in the coming months and years will determine whether nuclear is included in taxonomies and key finance frameworks. These decisions will guide public and private financing decisions for years to come with long-lasting impacts. The most efficient solutions to climate objectives will be best enabled by technology neutral taxonomies, climate finance, development finance, and ESG criteria.

Recommendation 6: Ensuring full representation in policy discussions about clean energy and climate change

Governments should break the silence on nuclear energy in policy discussions about clean energy and climate change, raising the profile of nuclear energy alongside other non-emitting energy technologies and ensure that nuclear is included in discussions at climate change conferences. Three key messages are of particular importance:

(1) **Nuclear energy already makes an important contribution to emissions reductions and it needs to expand to meet Paris Agreement targets.** Today, nuclear energy provides 10% of the world's electricity as the largest source of non-emitting electricity in OECD countries and second largest source of non-emitting electricity around the world, displacing 1.6 gigatonnes of carbon dioxide annually. The average IPCC 1.5°C scenario requires nuclear to reach 1 160 gigawatts of electricity by 2050, up from 394 in 2020.

(2) **Near-term nuclear innovations are expected to make significant contributions to emissions reductions targets.** Nuclear innovation in the areas of advanced and small modular reactors (SMRs), as well as nuclear hybrid energy systems, including hydrogen, is advancing quickly, with several SMR designs expected to be commercially deployed within 5 to 10 years, which could displace an additional 15 gigatonnes of carbon dioxide emissions by 2050.

(3) **Policies should be technology-neutral, structured to incentivize desired outcomes such as emissions reductions and security of energy supply**. This includes taxonomies, as well as criteria for access to climate finance (e.g. the Green Climate Fund), development finance (e.g. multilateral development banks such as the World Bank and others), and Environmental Social and Governance (ESG) finance. Metrics should be applied consistently with similar levels of scrutiny across technology options, to allow technologies to compete on equal footing. In this way, efficiency is best achieved with technology-neutral policies and criteria.

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